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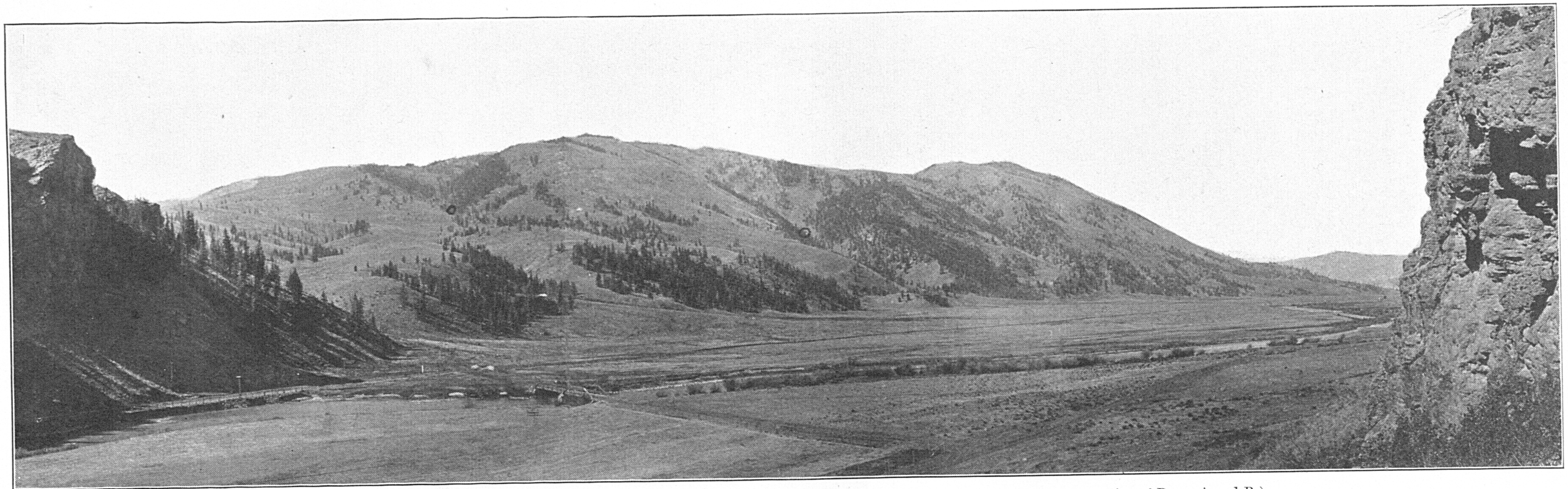


FRONTISPIECE—View of watersheds A and B, Wagon Wheel Gap. Rio Grande in foreground. (Heavy circles show location of Dams A and B.)

CHAPTER I.

HISTORY AND DESCRIPTION OF THE PROJECT.

INTRODUCTION.

The Forest Service, United States Department of Agriculture, planned as early as 1909, to make a very complete study of the effects of forest cover on streamflow and erosion, and tentatively selected a site for the experiment on the Rio Grande National Forest, near Wagon Wheel Gap, Colo. The plan, broadly stated, was to select two contiguous watersheds,[1] similar as to topography and forest cover; to observe carefully the meteorological conditions and the streamflow for a term of years under similar conditions of forest cover; then to denude one of the watersheds of its timber and to continue the measurements as before for an indefinite period, or until the effects of the forest destruction upon the time and amount of steamflow, the amount of the erosion, and the quantity of silt carried by the streams had been determined.

Since the plan contemplated the use of considerable instrumental equipment and the services of men skilled in meteorological observations, the cooperation of the Weather Bureau was solicited, and on approval of the Secretary of Agriculture, the two services began the active work of getting material and equipment on the ground on June 1, 1910. The building of cabins for living and office quarters, the installation of the meteorological instruments, and the construction of two dams occupied the time up to October 22, 1910, when the first meteorological observations were made. The rectangular weirs installed in the beginning did not prove satisfactory and it was not until the following July that satisfactory weirs were installed.

On June 30, 1919, eight years' continuous streamflow measurements and nearly nine years' meteorological observations had been obtained. A consideration of this material leads to the conclusion that the first stage of the experiment has been adequately developed; it has, therefore, been mutually agreed that one of the watersheds (B) should be denuded, except that a strip of timber not to exceed 25 feet in width should be left on either side of the stream for a single season, complete denudation to be effected in the autumn of 1920. The program of denudation at this writing has been carried out as planned. The larger timber has been removed from the area, while the loppings and most of the aspen have been piled in windrows and are eventually to be burned.

OBJECT OF THE PRESENT PAPER.

The object of this discussion is to give a clear idea of the nature of the experiment, the methods followed, the conditions observed to date, and the plan for analyzing the data obtained in the future so as best to bring out faithfully and clearly the effects upon streamflow and erosion which are produced by the denudation of one of the watersheds. Naturally, to be of tangible value, such effects must in some manner be shown quantitatively and statistically. It is especially to be hoped that the present discussion will bring out criticisms from irrigation engineers and others who are particularly interested in matters of water supply from mountainous sources, so that the final study of the results of the projects may succeed in presenting data of the most useful character.

CONDITIONS OF THE EXPERIMENT.

It is an open secret that foresters generally, and nearly all persons possessing familiarity with the conditions in mountainous regions, believe strongly in the protective value of forests, first, as binding the soil, covering it with humus and litter and preventing its erosion, and secondly as exerting a modifying effect upon the flow of streams. The latter is based primarily upon the very obvious fact that rainfall upon the floor of the forest is very largely absorbed by the covering of spongy material which is typical, hence does not immediately run off on the surface of the ground, but percolates into the deeper soil and maintains streams more evenly by feeding springs. A further influence in the western mountains of the United States is assumed to arise from the retardation of snow-melting which is a direct result of shading by the trees. In this particular respect forests, even deciduous forests, apparently have a value which no other form of vegetation could possess. Thus, by a number of means, it has been taken that forests reduce the magnitude of floods, tend to maintain streamflow, through springs, in dry weather, and, perhaps most important of all, prevent erosion of the land which they occupy, reduce the amount of silt carried by streams, and lessen the damage done by flood waters wherever these may inundate or erode fertile fields.

The present paper does not attempt to prove or disprove the above contentions, but simply to state them as beliefs which require experimental proof. Hence, there will be no attempt to cite here the great list of references which supply facts in the case, nor again the great list of arguments by those who have observed facts apparently weakening the beliefs of foresters. It must be admitted that the evidence upon which foresters have based their beliefs, and the evidence upon which a number of countries have formulated their policies of economic forestry, have been too largely empiric, just as has been the

[1] Throughout this discussion, and in all of the records the convenient and perhaps more popular word "watershed" is used to denote a drainage basin.

evidence on which farmers, up to a few decades ago, based nearly all of their agricultural practices. The present-day attitude calls for experimental proof of every belief, and, especially where great economic values are involved, calls for quantitative determinations. It is not enough to know *whether* forests influence stream flow; it is necessary also to know how much, at what seasons, and under what conditions of soil, topography, and geographical location.

Up to the time of the initiation of this project there had been but one serious attempt to measure the influence of forests upon streamflow, precisely and over a long period. The results of this experiment, which was made in Switzerland, after some 12 years of observation, have, fortunately, just been made available in an exhaustive and apparently unbiased report by Dr. Engler.[2] This may perhaps be considered the most authoritative statement on the subject ever published. Yet even here the results are largely qualitative, and even open to some question, for the simple reason that experimental conditions have not been fully attained. The two watersheds, one about wholly forested and the other only to a small degree (for what reason barren we do not know), were taken in their natural conditions, and comparisons of streamflow have been made only in this condition. Without questioning the immense value of the results, which have been secured, it may be freely said that the Swiss experiment leaves a certain want unfilled.

It was, therefore, with a full realization of the need for experimental proof, and in the hope of satisfying the most critical, that in 1909 the Forest Service undertook to initiate a project which should produce results bearing particularly on the conditions typical of vast areas then included in the national forests of the West. More recently, under the Weeks law, national forests have become a reality in the eastern United States, and it is but logical that the Federal Government should interest itself, as soon as practicable, in a similar study in that region.

In seeking an area for the experiment, as was done during the summer of 1909, the following were guiding considerations, their relative importance being indicated by the order in which they are named:

1. That the two watersheds to be studied should be contiguous, or practically so, in order that differences in the amount and time of precipitation reaching them should be as small as possible.

2. That the two watersheds should be on the same geological structure, should have similar altitudinal limits, and, as regards general conformation, general aspect, and steepness of gradients, should be as nearly alike as possible.

3. That the area of each watershed should not be so large as to introduce serious complications in the attempt to relate the stream discharges at the lower extremities to precipitation and other phenomena observed on the areas.

4. That the forest conditions should represent a fair average for the national forests of the Rocky Mountain region, rather than the ideal or optimum. Such a provision insures that the quantitative results may be applied to the national forest area as a whole, with conservatism. To meet this requirement it seemed essential, first, that the forest should be that of a middle elevation, and secondly, that it should not entirely have escaped injury by fires in the past.

5. That the areas should be accessible, so that one of the watersheds might be denuded without waste of the timber.

6. That the location should be reasonably near a town and railroad, so that the problem of keeping capable men on the project, and the problems of their existence, need not be insurmountable.

The areas selected.—Two areas apparently meeting all of the above requirements, with a minimum of compromise, were first visited in August, 1909.[3]

The size, shape, and general conformation of the two watersheds, hereafter to be known as A and B, are adequately shown on the accompanying map (fig. I). The survey on which this map is based was made by Engineer Niles Hughel, of the Forest Service, in June, 1910, and only slight changes in the delineation of the boundaries were made at a later date, at points where the exact water divides were vague and difficult of determination. The general plan of the survey was to start at the dam sites, tracing a line up either slope until the ridge was reached which divides one watershed from its neighbors; then to follow this lateral ridge to the head of the drainage basin. The principal errors made in the original survey resulted from the attempt, in one instance, to trace the divide from the top downward. In the reverse process there is practically no chance for error when each course taken is run normal to the contour at the point of origin. In the present case the distance, azimuth, and vertical angle of each course was recorded, so that the basic data for a contour, as well as an area map, were secured. The boundary traces were supplemented by traverses through the center of each watershed, following the course of the stream.

The springs or stream sources shown on this map were located only approximately, by reference to earlier survey stakes, by one of the writers, in 1913.

According to the accepted boundary survey, the areas and dimensions of the two watersheds are as shown in Table 1.

[2] Engler, Arnold. Experiments Showing the Effect of Forests on the Height of Streams. Mitteilungen der Schweizerischen Centralanstalt fur das Forstliche Versuchswesen. XII, 1919, Zurich.

[3] The writers wish to acknowledge at this point the interest and excellent judgment displayed by Forest Assistant P. T. Coolidge, of the Rio Grande National Forest, who was the real discoverer. The areas were visited again in February, 1910, by several officers of the Forest Service, and the selection was approved after the visit of Assistant Forester E. E. Carter at a slightly later date. The photographs used as the frontispiece of this paper were taken in February, 1910, by the late Varela, photographer of the Forest Service.

TABLE 1.

	A	B
Total area............acres..	222.5	200.4
Extreme length........feet..	7,300	4,600
Computed mean width.feet..	1,328	1,898
Absolute elevations....feet..	9,373–11,355	9,245–10,952

The greater area of A as compared with B, as above indicated, is of no appreciable import. That which is of importance, in so far as it complicates the relationship of the discharges of the two streams for any short period, is the fact that watershed A is considerably longer and narrower than B, and includes a small area extending to an elevation about 400 feet higher than any part of B. As will be seen later through consideration of the discharge graphs, for the purpose of discharging any single supply of water (such as the fall of a single rain), watershed A might be compared to a narrow trough and watershed B to a fan-shaped collector. The former, on account of its relatively short slopes, is able to deliver the first bulk of a water supply in a relatively short time, and this quick delivery is the basis for a sharp and high flood crest in most cases; yet on account of its length, this area may continue to deliver water to the dams for a long time. By comparison, B delivers its water to the dam after a longer interval, but more largely in one mass, and completes its discharge sooner. Were we ever dealing solely with the water of a single storm or a single period of snow-melting, the relations above set forth might not be difficult to express by a concise formula. But, since the streamflow of any period we may choose to consider is necessarily built up from water contributions of many previous months, it becomes apparent that the watershed differences have introduced a maze of relationships we can not hope to unravel or to give expression to, except in approximate terms. The great difficulties of this situation, of course, could not be foreseen when the watersheds were chosen, nor is it at all certain they could have been avoided, as Nature has nowhere been so kind as to form two objects exactly alike.

Of some slight importance, as it affects snow-melting, is the fact that the main axis of watershed A is almost directly east-west, while that of B is more nearly northeast-southwest. In consequence, the north half or southerly exposure of A contains considerable areas which face squarely the mid-day sun, while on B the corresponding position is very largely an east slope, except for a very small space at the lower end of the watershed. After a very careful survey of the several snow-scale areas, Keplinger (Apr. 1, 1913) computed the mean gradient of watershed A to be 25 per cent and of B 26 per cent; but the mean aspect of all the slopes on A is S. 85 E., while on B it is N. 68 E.; a difference of 27 degrees.

Geological formation.—As has been stated, one of the first considerations was that the two areas studied should have similar geological origins, not only because the character of the rock defines the physical character, permeability, and retentiveness of the soil, but also because the present rock *in situ* has the greatest influence on underground water and on the possibility of complete measurement of the water discharged from the areas.

The first geological examination of these watersheds was made by Mr. E. S. Larsen, of the Geological Survey, in June, 1910, or while the first prospecting for the dams was under way. It is regretted that we can not quote here Mr. Larsen's original report, which was entirely reassuring, both as to the uniformity of the structure on the two areas and the probabilities of a structure at the proposed dam sites which would insure a good foundation for the dams and the loss of none of the water which flows away from the areas.

It is, perhaps, equally satisfying to have a later report by Mr. Larsen, made at a time when some neighboring areas were being considered for supplementary study, and when some rather definite problems with respect to A and B had presented themselves:

SUPPLEMENTARY REPORT ON THE GEOLOGY OF THE AREAS COVERED BY THE WAGON WHEEL GAP EXPERIMENT STATIONS, RIO GRANDE NATIONAL FOREST, COLORADO.

By ESPER S. LARSEN.

INTRODUCTION.

JUNE 20, 1914.

The present report contains the results of a few days' study during June, 1913, of the area near the experiment station and has to do particularly with the two new drainage basins E and F, although some phenomena of the other drainage basins are discussed.

GEOLOGY.

Drainage basins E and F are in the same type of augite-quartz latite which forms drainage basins A and B. This member also forms all the slopes between the several drainage basins, the slopes for some distance above the upper basins, and the basin of Deep Creek to the main forks of the creek about a mile above the mouth. In the fork of the Deep Creek, on which drainage basin F is located, this latite extends from an elevation of about 8,800 feet to 12,000 feet or more, a vertical extent of over 3,000 feet, and neither base nor top are exposed. The rock is nearly uniform, and, although exposures are fairly good in Deep Creek, no evidence was seen of more than one flow,

The petrographic description given in the previous report covers the member as a whole. In the former report it was said to probably overlie the tuff, but a more extended study about Creede and elsewhere has shown that the tuff was deposited in a steep-walled basin of the augite-quartz latite.

The rock has a poorly developed flow structure which is nearly flat. The general dip of the flow lines could not be positively determined, but it is believed to be generally to the north. A fairly prominent, nearly vertical, closely spaced sheeting is also common. This sheeting, and, to a less extent, the flow structure, would exert some influence on the flow of the underground water, but, so far as observed, the structure is not regular enough to determine the direction of the flow. The rocks are probably fairly tight and impervious below the zone of weathering.

Both drainage basins are almost completely covered with a relatively thin mantle of soil and decomposed rock, which is usually porous and of sandy texture, with some clay and numerous flat fragments of the underlying augite-quartz latite. Judging from the few pits and natural exposures, the soil is believed to be very shallow and to grade rapidly into rock in place. The upper few feet has probably moved somewhat by creep. The fractures due to weathering continue for some depth into the rock in place. Actual outcrops of the bedrock are rare, but it is nowhere believed to be far below the surface. Landslides or considerable-sized bodies of wash, talus, or alluvium are not present. The small parks and still smaller strips along the creeks are the most important accumulations of alluvium, and these are not believed to be very deep.

UNDERGROUND DRAINAGE.

Except for the creek bottom park in basin E, the geological character of two basins, E and F, is nearly identical and very similar to those of gullies A and B. The soil and the immediately underlying disintegrated rock are rather pervious to water, but I believe that the fresh, little fractured rock at no great depth is much less pervious. The conditions are almost identical with those of the two lower basins (A and B) and the discussion in the previous paper applies equally well to all four drainage basins.

I believe that the geology of the areas covered by the four basins is very favorable for the experiments. It is unusual to find four areas with so great a difference in elevation yet so uniform geologically, and with so little variety or structure in the rocks. So far as I can judge, the basins are all exceptionally favorable for the minimum loss or gain of water from the underground drainage, and there is nothing to indicate an exceptional loss or gain for any of the basins.

HOT SPOTS.

The so-called hot spots on the east side of the slope of basin A were recognized by Mr. Jones, of the Weather Bureau, who is located at the station, from the fact that the snow melted more rapidly along them. They appear to be on a line nearly parallel to the creek and about 50 feet in elevation along it, and extend from the north boundary of the area for about a hundred yards to the south.

Bed rock is not exposed near them, but the talus indicated some alteration of the rock, such as is commonly found associated with mineral deposits. A small cut exposes rock which has crept down the hill somewhat, but which is nearly in place. There is a little red hematite coating the fragments and some travertine-like materials. The rock is kaolinized and has some hematite deposited in it. There is no evidence of water, steam, or other gas coming up here.

I have no entirely satisfactory explanation of this, but three possible ones occur to me:

1. The oxidation of stringers of pyrite or other sulphides may generate enough heat to slowly melt the snow over a series of veinlets.
2. There may be fractures along which warm water or gas is escaping.
3. Fractures in the rock may control the circulation or underground air currents.

If the first is true, and the hematite indicates this, there is probably a strip of more or less fractured rock present and the water will tend to drain into this strip and along it to a lower level on the hill. This would tend to steal some water from the drainage area, as the fracture crosses the lower boundary of the area on a rather steep and continuous slope.

If the second explanation is true and a considerable amount of the water is being introduced into the drainage area, some evidence of this should be recognized. If the hot water escapes at a lower level on the slopes, that is, below the drainage area, and the melting of the snow is due to gases escaping through fractures, the conditions are similar to those discussed in the first explanation and there would be a loss of water.

Explanation 3 would also cause a loss of water much as would 1.

WARM SPRINGS.

The large spring which empties into basin B from the west and which has a mean temperature several degrees in excess of the mean annual air temperature has all the appearances of a normal spring. The presence of hot springs only a mile or so away immediately suggests a deep source for at least a part of the water of this warm spring. However, I should not expect such water on these steep slopes, as valleys nearly a thousand feet below are present on three sides only a short distance away. A comparison of the composition of the water from the spring with that from the creek would probably show whether or not any ascending hot water mingled with the surface drainage water.

To this report the following facts should be added:

1. At the site chosen for a dam on watershed B rock *in situ* was found, as expected, beneath only 4 to 6 feet of talus and stream deposits. This rock was only slightly fissured, and the fissures were in no case open, but well filled with clay, so that there was never any serious question as to the practical impermeability and complete solidity of the dam foundation.

2. At the site chosen for a dam on A, rock *in situ* was found on the north bank of the stream, as expected, but not on the south bank. Apparently the present channel of stream A is a considerable distance above and to the north of the notch cut in the bedrock in primary erosion. This is due, no doubt, to a land-slip from the slope to the south. A short distance upstream from this dam there is at present a "rock-slide" jutting out to the stream, which illustrates clearly the nature of such movements. By great good fortune, however, there was at Dam A, at about the depth where bedrock was expected, a ridge of clayey material parelleling the stream and apparently deposited there by the stream in the loose structure of the earlier rock-slide. While not entirely impervious, this dike afforded the only possible foundation. The main cross-channel wall of the dam was built somewhat beyond it into the loose material of the land-slip, and a wing-wall was run on its crest to a point upstream where the elevation of the original dike was that of the top of the dam.

3. On the areas E and F which are mentioned by Larsen in this report rock *in situ* was found at no great depth but was badly fissured and carried so much water that the project of building additional dams had to be given up.

As regards the actual success attained in trapping all of the run-off of watersheds A and B at the dams as constructed, the greatest assurance is found in the fact that, year by year, the ratio of run-off to precipitation for the two areas is practically identical. While it would be possible to have leakage at both dams, and in the same amount, such coincidence is certainly improbable. Actual proof that all run-off is being measured could of course only be obtained by a number of deep borings in the bedrock.

Soil of the areas.—The augite-quartz latite described by Larsen as comprising the entire foundation of the two watersheds, by reason of its fine crystalline structure breaks down into a rather fine and compact clayey loam. On account of the steepness of most of the watershed slopes, however, this quality is only partially developed; that is, steady sheet erosion prevents the accumulation of deep masses of soil and insures that rock fragments shall comprise a very considerable proportion of the mass, sometimes as much as 50 per cent of the whole if the first 4 feet of soil are considered. In addition, erosion and leaching tend always to rid the soil of clay and silt, while leaving the coarser sand. The result is, on all the steeper slopes, a quite permeable and well-drained soil layer. The depth of this layer on the main slopes has never been investigated directly.

It is believed the figures in Table 2 represent fairly the nature of the soil derived from the quartz-latite, except for station A–1, where the soil was taken from a pocket nearly devoid of rock fragments.

As contrasted with this, the soil of a bench immediately below watershed A, which represents the transport from the slopes of the watershed, has been examined. This contains only 2.1 per cent rocks, 7.1 per cent fine sand, and 80.0 per cent very fine sand, silt, and clay.

The soil of these areas is, then, fairly permeable, but certainly of as fine and retentive a character as the average for middle elevations in the Rocky Mountains.

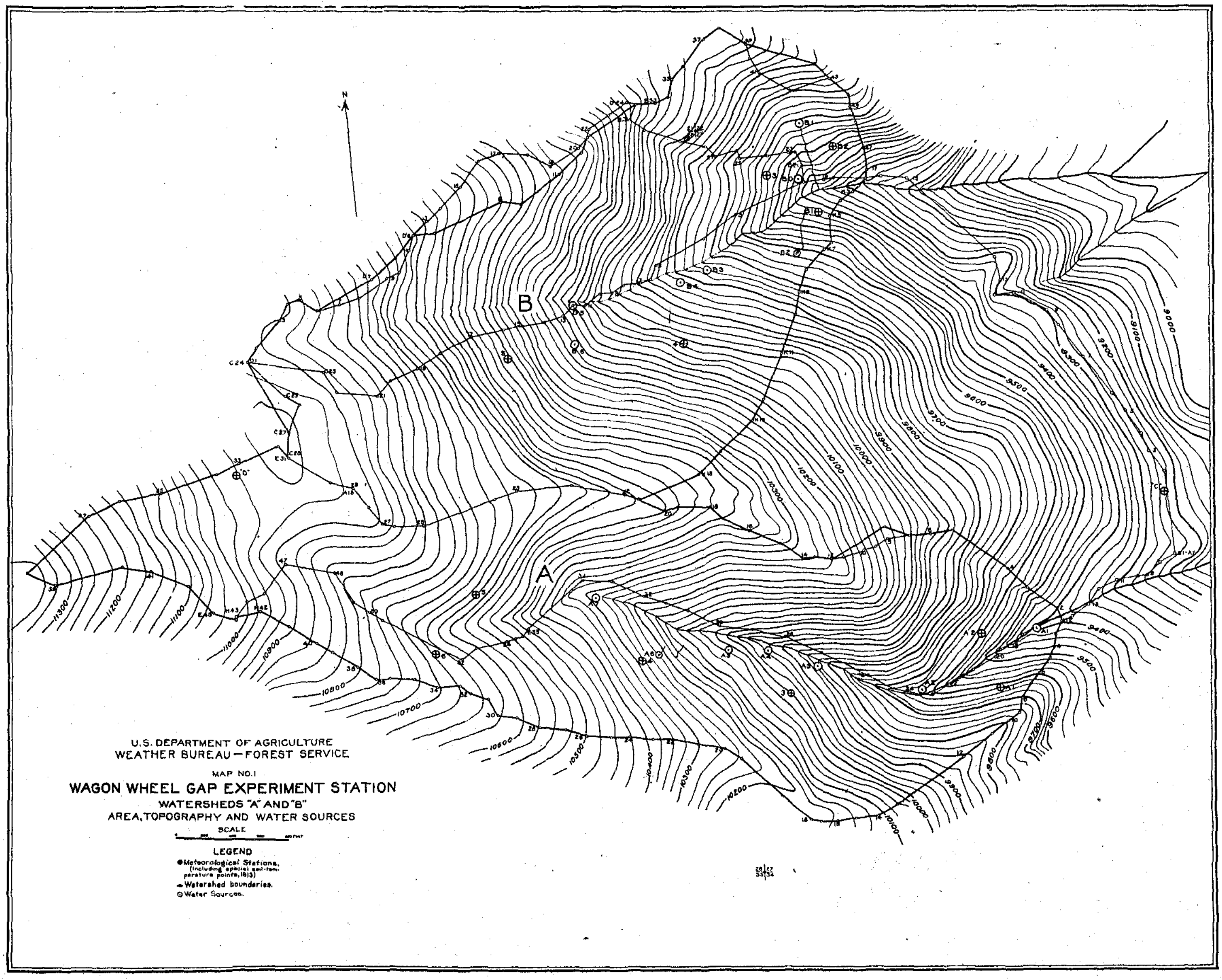


FIG. 1. Area, topography, etc.

TABLE 2.—*Soil composition of bench and slopes.*

Class of material.	Station D.			A–1.		A–2.	
	1 foot.	2 feet.	3 feet.	1 foot.	4 feet.	1 foot.	4 feet.
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Rocks larger than peas	14.2	47.4	34.5	11.4	10.6	30.8	26.7
Coarse gravel	8.0	2.6	1.7	11.2	21.5	17.8	29.0
Fine gravel	6.8	1.4	3.2	9.6	17.6	7.0	10.4
Coarse sand	11.0	7.5	9.9	19.6	18.6	8.8	8.6
Medium sand	6.6	6.0	7.0	10.7	7.9	5.1	3.7
Fine sand	5.4	4.8	5.9	7.4	5.1	4.0	2.7
Very fine sand	11.7	8.4	10.8	8.1	6.3	7.1	5.1
Silt	29.3	16.8	22.2	14.5	7.8	15.6	9.4
Clay	7.0	5.1	4.8	7.5	4.6	3.8	4.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Water sources of the streams.—On the map which shows the outline and topography of the watersheds, Fig. 1 the principal springs which feed the two streams have been indicated, as also some special observation points which were used in a study of these water sources in 1913. The latter should not be confused with the regular meteorological stations and snow-scale locations which are shown in another map.

Examination of the map will show that stream A first appears about 3,500 feet from the dam, and is fed along its course by some half dozen springs, only two of which make their first appearance at any appreciable distance from the main channel.

Stream B has a total length of only about 2,300 feet, and in this distance becomes submerged several times in the detritus of the main gully.

Kadel and Grove, in 1912, measured the exposed areas of both streams, including water-soaked ground along their margins, and obtained figures of 4,039 square feet for A and 1,600 square feet for B.

Stream B, like A, has several springs along its course. One, near the head, appears at least 500 feet from the channel, soaks into the ground, and comes out again as channel seepage. Another, near Station B–1, appears still higher on the northerly slope. The really striking difference between the two watersheds, however, is in the existence of the permanent and voluminous spring shown as B–1, and the temporary spring B–0, both *appearing* to arise from ground with a decided southerly exposure.

The warmth of the spring B–1, which is mentioned in the geological report that has been quoted, has excited so much comment and fear that it was thought best to obtain, in the summer of 1913, some data on its actual temperature, the temperature of the ground in its vicinity, and comparable data for the other water sources. After locating the latter, therefore, points were very carefully chosen which, it was thought, would represent the ground drained by the several springs. Thermometers were placed at a depth of 1 foot at each of these points, and additional thermometers at 4 feet at only a few points, which were thought sufficient to give the temperature gradient in the soil. The temperatures of the springs were likewise measured. For the most part, results were obtained by observations every few days, at different hours, so that diurnal fluctuations were pretty well taken care of in the averages secured. The observations were necessarily subordinate to the other work which was being conducted, were irregular in interval, and are not entirely synchronous for all of the points.

The following points are noteworthy:

1. The 1-foot soil temperatures of the two watersheds are very similar if we consider only the northeasterly aspects. In the case of watershed B, however, the principal water sources are in ground with an easterly or somewhat southerly aspect, so that the mean temperature of all the contributing ground is about 2° higher than in the case of A.

2. In spite of this warmer soil for B (as a whole) the mean temperature of all of the springs on B is 0.6° less than that of the springs on A at midsummer.

3. When it is considered that the reverse is true in winter—that stream B is warmer than A as shown by ice formations at the dams—the conclusion is unavoidable that the water sources of B are *deeper* than those of A.

4. Applying the mean difference of 7° F. between 1-foot and 4-foot temperatures for this period, it may be calculated that the soil reservoir of A has a mean depth of about 4.8 feet, and of B about 5.8 feet. Actually, of course, it may be deeper in both cases, as the spring water can hardly fail to be warmed somewhat as it approaches the surface.

It is not suggested that the corresponding steep slopes of the two watersheds are essentially different as regards soil cover. It is believed the difference consists in a greater accumulation of soil near the stream channel, in the bowl-like basin of watershed B.

5. Considering the several water sources independently, rather consistent depths are indicated. The two south-slope springs on B (B–0 and B–1) would appear to have deeper sources than the others, but only about 6.5 feet as indicated by the conditions in July.

It has been contended, by those inclined to view the existence of the warm spring (B–1) with alarm, that, since the mean annual air temperature on these watersheds is only 34° F., water which shows a temperature of nearly 40° F. at midwinter must be arising from a source so deep as to be unaffected by local conditions, or else must be obtaining heat through some chemical reaction. The latter idea must be banished when it is noted that there is not the slightest evidence of deposits on the ground over which the water trickles for several hundred feet, and the water is not in the least inimical to plant growth.

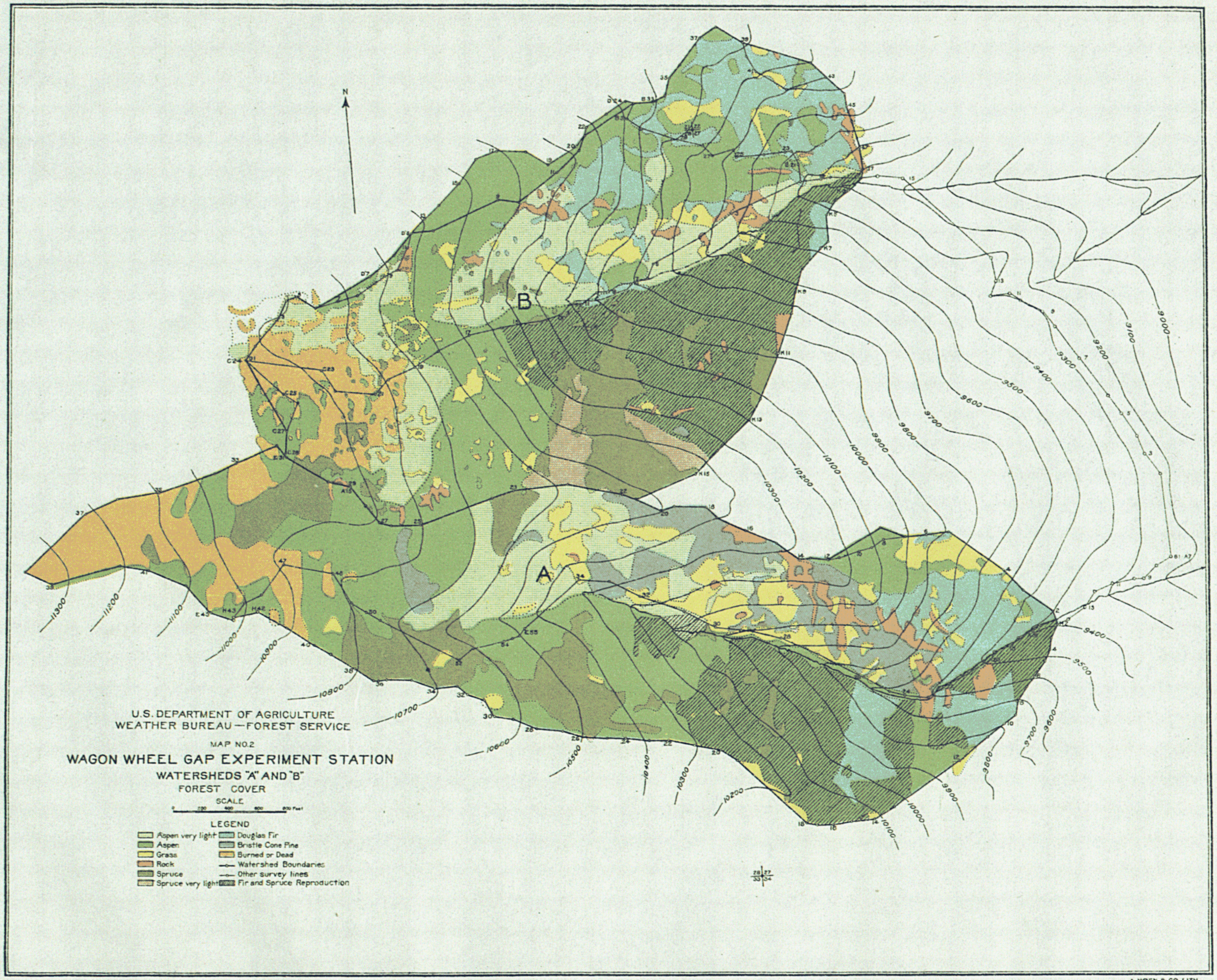
Although, as stated by Moore [4] it is altogether probable that at a considerable depth (say 50 feet) the ground temperature is constant and approximately equal to the annual mean temperature at the surface, still there is no basis for the assumption that the latter must be the mean *air* temperature of the locality. The mean air temperature of 34° F. is recorded at the north-slope station, B–1. The mean 1-foot soil temperature at that point is 34.3° F. and the 4-foot soil temperature 33.3° F. On the other hand, while the air temperatures recorded for a year or more at the south slope station B–2 were only about 2° in excess of those at B–1, the 1-foot soil temperature is 39.7° F. and the 4-foot 40.6° F. There is no reason for supposing that a lower mean temperature is found at greater depths. There is every reason for supposing that at a depth of possibly 20 feet the soil temperature on this slope is essentially 40° the year around.

As to the assumption that the water which feeds this spring must be transported a great distance through rock crevices, there is again no evidence in proof. The east slope above this spring retains its snow well, is well forested, and is of sufficient area to supply the water. The only oddity about the spring consists in the fact that it rises to the surface in a relatively shallow depression facing the south, instead of first appearing in the more distinct gully at the foot of the east slope. It does not, however, have to perform any miracle to reach its outlet.

In conclusion, then, it may be said that without much doubt the "warm spring" reflects only the temperature

[4] Moore, Willis L. "Descriptive meteorology." New York, 1910.

FIG. 2



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of the ground from which it rises, and its point of origin, while doubtless affected by rock conformations that are not apparent on the surface of the ground, is not more enigmatical than is general in the occurrence of springs.

It might be noted that early in the study of these water sources, one of the writers thought that a similar water source had been discovered on watershed A, at the foot of a rock-slide which faces the southeast. (See water point A–2). This consisted of a spring on the north bank of Stream A having a temperature early in July of about 44. By testing with methylene blue, however, it was found that this was merely a portion of the main stream which had found a course under the toe of the rock slide. That the north half of watershed A contributes through no springs of noticeable size is plainly due to the rapid melting and evaporation of snow in the winter, because of the more southerly exposure of this ground as compared with any part of B.

6. Comparison of the average spring temperatures with those of the streams as they approach the measuring dams shows that the water of either stream is warmed about 3.8 ° during its passage down the channel. This is after making allowance for the fact that the 9 a. m. temperatures at Dam A were nearly a degree lower than the mean of maxima and minima, while at B the water has attained nearly its mean at 9 a. m. In spite of the fact that the exposed area of stream B is much less than that of A, the water is warmed as much. This is probably because the volume traveling the main channel is slightly less, and all but two of the springs of B watershed flow over the ground for considerable distance before reaching the main channel. In view of these facts, we should expect just as much loss by evaporation during the day on stream B., but possibly would note the loss at a later hour, because of the impeded flow. The delay may run so far into the night as to really obscure the amount of the evaporation current during the day.

Description of the forest.—The forest of the two watersheds involved in this study is one fairly typical of the middle zone of the central Rocky Mountains and is characterized by the predominance of Douglas fir.

On account of the character of the soil derived from a fine-grained igneous rock, western yellow pine is practically nonexistent in this locality and does not appear on the lower reaches of the watersheds at all, though in most of the region it would be expected on southerly exposures at this elevation. Such exposures are occupied almost wholly by Douglas fir of good development, but forming open stands. There is everywhere a sprinkling of bristlecone pine, which becomes more numerous at the tops of the slopes and wherever the amount of rock in or on the soil is very great.

The northerly exposures at low elevations are also characterized by fir stands, more dense, of course, than those of the warm slopes. There is everywhere a sprinkling of Engelmann spruce, and with increased elevation the proportion of this species increases, so that at the upper extremities of both watersheds the type is almost pure spruce.

A large part of watershed B, and only slightly less acreage in A, was burned over, as nearly as can be determined, about 1885. While the fire may or may not have run through the stands on the southerly exposures, their open character prevented serious damage, and such areas may be considered to be now in an essentially normal state as regards cover. Much greater damage was done to the north-slope fir stands, on practically all such acreage of watershed B, and in strips on the lower portion of A, while the prime spruce forest at the upper ends of A and B was almost completely destroyed, and a considerable part of this area is not now covered even by aspen, except in occasional clumps.

Throughout most of the lower areas which were severely burned, aspen appears to have come in promptly and densely, so that the typical forest-floor conditions have not been lacking during any stage of the experiment, and the soil has been sufficiently bound and covered that practically no surface run-off or erosion has been noticeable. However, it should be realized that the extensive areas of aspen which particularly characterize B can not possibly have the effect of retarding snow melting that would be exercised by an even stand of coniferous trees. For this reason it is felt that whatever contrast is secured from the denudation of B will represent a very conservative measure of the normal effects of Rocky Mountain forests.

Over a good portion of the aspen-covered area of both watersheds coniferous seedlings had begun to appear even before the initiation of this experiment, and by the time of its completion these will have attained sufficient size and numbers to exercise a quite appreciable influence on their environment. In other words, forest conditions on watershed A during the progress of the experiment have been in a constantly improving state, approaching normal. On the other hand, the extreme upper portion of A, which has the greatest potentiality as a snow reservoir, remains uncovered, except for about an acre of lodgepole pine plantation started in 1911, whose effect even after many years must be insignificant.

On both watersheds there are some small areas of essentially barren rock slides, whose tendency, no doubt, is to bring snow and rain water to the streams more directly and quickly than the areas covered by a normal soil.

The distribution of the different kinds of cover is best seen by reference to the forest-cover map (figure 2), prepared by the Forest Service from data collected by Keplinger, mainly in 1912. Figures 3, 4, and 5 further illustrate the conditions of forest cover in the watersheds. A summary of the different types gives the comparison of the two watersheds shown in Table 3, from which it will be seen that the principal difference is the substitution of bristle-cone pine for some aspen on watershed A.

TABLE 3.—*Forest cover of the watersheds.*

Type of cover.	Area, percentage.	
	A.	B.
Burned (mostly spruce type)	9.5	6.6
Barren or rock slide	2.7	3.0
Grass covered	9.4	6.1
Aspen without conifers [1]	34.3	43.8
Aspen with conifers	14.4	17.1
Douglas fir	8.8	11.4
Mainly spruce	11.9	12.0
Bristle-cone pine (open)	9.0	......

[1] Conifers hardly large enough to exert any influence.

INITIAL WORK AND DAM CONSTRUCTION.[1]

The actual work of initiating this project was begun by B. C. Kadel of the Weather Bureau and C. G. Bates of the Forest Service about June 1, 1910. There had previously been constructed, to the site of the headquarters, a wagon road from the railroad station at Wagon Wheel Gap, under the direction of Supervisor Shoup of the Rio Grande National Forest, and the same crew of workmen, after June 1, built various local trails and erected an office building. Contracts were let for two dwellings. The time of Mr. Kadel was largely devoted at the outset to the boundary survey, and later to the innumerable tasks incident to installation of the meteorological apparatus and stream-measuring devices. The construction of the dams was left largely to Mr. Bates.

As the entire success of the experiment may be said to hinge on the structure of the dams and stream-measuring devices; the form of the dams and the method of their construction will be dwelt upon in considerable detail. We have already described the rock conditions encountered at the dam sites.

The primary consideration was to construct a wall across either stream channel by means of which both the surface and subflow of the channel could be collected for measurement. This was accomplished, after digging the cross trench down to a solid foundation, by pouring a solid concrete wall to a height at least a foot greater than that of the original stream channel, except at the center of the channel, where a notch was left through which the stream might flow. The thickness of this wall was 8 inches, except at the bottom, where the concrete was allowed to spread out the full width of the trench. The mixture used was about one part Portland cement to five parts of sand and gravel, insuring practical impermeability, except for an amount of "sweating" too small to be measured. The lower portion of the wall was necessarily "poured" under some water, as the pump available would not keep the trench dry, and the wall was subjected almost immediately to some hydrostatic pressure. By means of the diverting pipe, however, the stream was carried to a considerable distance down the channel and ample opportunity was had to note that no leakage through or around the wall developed.

[1] See half tone figures 8–14.

Having thus made possible the concentration of all the flow at a single central point in the channel, the next step was to provide means by which the amount of the flow might be measured. A consideration fully as important was to be able to trap, by settling, all of the detritus carried by the streams, and which would have no difficulty in passing over the dam wall. The basin below the dam, then, while essential to precise measurement of the flow, is primarily a settling basin.

This basin is in each case nearly 25 feet long (lengthwise of the channel), 6 feet wide at the upper end where it joins the dam, 18 feet wide at the lower end, and with walls 4½ feet high. These lateral and end walls were made 5 to 6 inches thick and plastered with two coats of 1–1 cement plaster. The floor of the basin was poured about 4 inches thick after pounding rock into the rather loose foundation. This was also plastered.

The shape of the basin, flaring at the down-stream end, was dictated solely by the conformation of the ground. The down-stream wall abuts upon a log cribbing filled with rock and earth, which comprises a secondary dam or support for the whole structure, in anticipation of floods which might exert a very real pressure.

In the lower wall and in the log crib which reinforces it there was left an opening 4 feet wide. The opening in the concrete wall was really two openings, separated by 12 inches of concrete. These two openings comprised parallel channels 12 and 24 inches wide, respectively. The narrower of these had its opening about 3½ feet above the basin floor and the wider one 4 feet. The lower line in each case was defined by a horizontal straight-edged steel weir plate. The plan was that the water should flow over the lower weir plate, through the 12-inch channel, until the volume was sufficient to make a stream more than 6 inches deep, after which the wider channel and higher weir would automatically come into play. This plan was made with no foreknowledge of the flood volumes to be expected. Actually, the capacity of the 12-inch weir was more than necessary, and at the low heads of late summer and winter the stream flowing over it was so shallow as not to carry off properly, and precise computation of the volumes discharged was impossible. After a year's trial, therefore, or about July 1, 1911, there was substituted in each basin a triangular or notch weir.

The new weir plates were cut 4 feet wide, so as to cover the entire area of the two original openings and the division wall, the latter being removed. The depth of the plates is 30 inches and the thickness one-half inch. The notch, figured from the top edge of the weir plate, is 18 inches deep and 36 inches wide, the angle of the notch being 90°. The edges of the notch were beveled back about 2 inches and ground to a thickness of one-sixteenth inch. The great advantage of these weirs lies in the fact that the smallest volumes with which we have to deal create a stream of sufficient depth at the bottom well

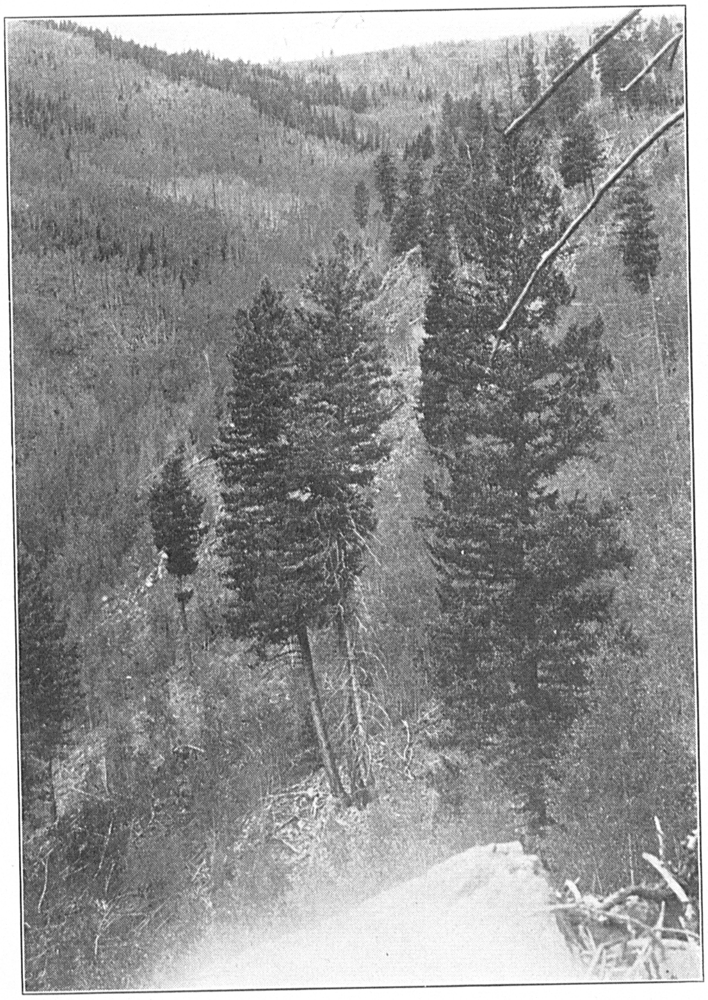

Fig. 3. Watershed B near station B-2 showing large extent of aspen with small conifers.

Fig. 4. Conditions in a young coniferous stand, typical of much of the upper portion of watershed A.

Fig. 5. Rather large Douglas fir surrounding thermometer shelter at station A-2.

away from the face of the plate, and at the same time the entire opening possesses a very large capacity.

As will be shown later, the measurement of streamflow volumes in this case is based upon the height of the stream over the weir. The zero of height measurements is the lowest point in the weir notch. The height of the water, from which the volume of flow is computed, is determined several feet back from the weir, or in the center of the settling basin, where there is no appreciable current. The settling basin is, therefore, essential to the precision of flow measurement which this study called for.

Less essential features of the dams are the basin intakes, the diverting pipe and the tail-race. These are all 4-inch iron pipes. As has been stated, the original plan was to have the stream enter the basin through a notch in the concreted dam wall. A little to one side and about 6 inches lower was the opening of the diverting pipe, by means of which the stream might be diverted around (to be exact, the pipe runs through) the basin when the latter was to be cleaned, or any other operations in the basin were necessary. When the cap was placed on this pipe, naturally a small amount of water had to accumulate before the stream began flowing over the dam, or, in other words, this arrangement necessitated the existence of a small pool above the dam, in which the coarser material carried by the stream was deposited. When the diverting pipe was again opened, such material was inevitably carried away by the lowering of the water level in this pool, and the material was lost as a part of the silt accumulation. To overcome this difficulty, in 1913 there was inserted through the dam an additional short pipe to comprise an intake to the basin. This is at the same level as the diverting pipe. There is left, therefore, no cause for an accumulation of either water or sand above the dam. Diversion of the stream is accomplished by merely removing the cap from the diverting pipe and placing it on the intake pipe. It will be understood, of course, that the intake pipe may not be able to carry the entire stream in flood stage, the water still having access to the large notch in the dam.

The so-called tailrace is merely a pipe so placed as to carry away the water as it falls from the weir, with a minimum of splashing and with the object of preventing the formation of ice about the weir in cold weather. This pipe leads the water underground many feet away from the dam, where it may be emptied into the natural channel of the stream.

The settling basins were originally protected by means of joists and sheeting, with a flat cover which would exclude sticks and other foreign matter that might clog the weirs and which would also prevent dirt from washing over the walls and would eliminate wave-action in the basins from wind.

In the case of Dam A it has been necessary to supplement this by a housing which would further conserve the heat of the water, and in severe weather to create some artificial heat under this housing, in order that the flow at the weir and the height measurements might not be interrupted by ice formation. That there has been practically no difficulty of this kind at Dam B is due, no doubt, largely to the warmth of one of the stream tributaries, and in small part to better insulation of the dam throughout the winter.

SETTLING BASINS AND SILT MEASUREMENTS.

The effectiveness of the basins herein described in collecting the solid matter brought down by the streams is, of course, dependent primarily on the time allowed for such material to settle. The basins were originally designed to be proportionate in capacity to the watershed areas. Actual measurements in July and September, 1913, however, after the above-described changes in the weirs, etc., showed the slight discrepancy noted in Table 4.

TABLE 4.

	Basin capacity.	
	Cubic feet.	Cubic feet per acre of watershed.
Dam A	824	3.703
Dam B	772	3.852

These figures represent the capacities to the lowest points in the respective weir notches. Actually, of course, the basins always held at least 5 per cent more water than is indicated; relatively, the capacity of B is 4 per cent greater than that of A.

Computed from a mean annual flow of stream A of 553 cubic feet per hour, the above capacities mean that under average conditions the water in the basins is replaced about once in every 89 minutes, or flows through the basins at the rate of 1 foot in 4½ minutes. Actually, there is probably always a main current from the intake to the weir of much greater velocity than this. In flood times the periods might be reduced to one-tenth of these mean values.

Even in flood times, however, the basins have seemed to be very effective in clearing the water of its burden, except for a small amount of very fine and light organic matter. Actual study of the water which passes over the weirs was not made until the spring of 1920. The evaporation of the samples then taken indicates that the water carries a very trifling amount of silt at ordinary stages, but possibly at all times about 0.01 per cent of *soluble* matter, which, of course, no settling would eliminate. This would amount, in one year, to approximately 30,000 pounds of solids for stream A, or 20 to 50 times the weight of the silt collected in the basins. This seems startling, but it should be remembered that this load carried away by the water, of which we have no record, is quite independent of any surface erosion, and it is not seen that it could be greatly affected by the presence or absence of forests.

The silt accumulated in the basins is now actually measured three times a year, or about April 15, July 15, and October 15, in the following manner:

1. The stream is diverted around the basin.
2. The water in the basin is siphoned out.
3. Such water as can not be siphoned out, together with the solid matter, is shoveled into buckets and these in turn are emptied into large flat pans. Some water is added with the final sweeping of the material toward the lowest point in the floor.
4. The material in the pans is allowed to settle and some water is drawn off day by day. Finally, that which remains is allowed to evaporate, until the solid matter becomes dry enough so that it can be readily handled in sacks.
5. The moist material is spread on the floor of a drying-shed. When fully air-dried, the total weight is obtained and two samples are taken from the collection for each basin.
6. The moisture content of these two samples is determined through drying in hot-water-bath oven, and the net oven-dry weight of the whole collection may then be computed.
7. As a matter of possible further interest, the organic content of these oven-dry samples is determined by ignition at red heat. The mineral residue is retained for future reference.

LOCATION, EQUIPMENT, AND PERSONNEL OF OBSERVING STATIONS.

In the beginning it was thought advisable to establish six primary meteorological stations. One is near the office and living quarters and is called the C station; there are two on each of the watersheds, and the last is on the extreme upper portion of A, to represent the higher altitudes of both watersheds, known as the D station.

The primary stations on both watersheds are situated near the lower boundaries, one on the north slope and the other directly across the ravine in which the stream flows, on the opposite slope. North-slope stations are known as A–1 and B–1, south-slope as A–2 and B–2. The two pairs of watershed stations are the most important, and for this reason the location of these stations was selected with great care, the object being to secure as nearly identical conditions of topography and timber cover as possible. A–1 occupies about the same topographical position in Watershed A as B–1 in Watershed B, and A–2 the same as B–2.

The general topography of the watersheds and the location of primary and secondary stations are shown on figure 17. (See also Fig. 1).

The forest cover at all four of these stations was as uniform as it was possible to find, but even so, there are slight differences in the stand as follows: B–1 densest, A–1 second, B–2 third, and A–2 fourth. All stations are in Douglas fir stands. Station D is in a burned area, and Station C is outside the experimental area and the timber. In the office quarters at this station are housed the automatic registering instruments that record sunshine and rainfall at the C station and wind velocity and rainfall at D.

Station A–1.—Station A–1 is 700 feet S. 40° W. of Dam A, and 9,601 feet above sea level. The station is on a steep slope, angle 31° 20′, azimuth N. 24° W. Directly west of the thermometer shelter is a large open rock slide. While the surface of the ground at the station has a shallow covering of moss and fir needles, there is very little soil in the ordinary meaning of that term. Three or four inches below the surface small loose stones are found which can be removed by the hands. At this particular spot the interstices between the stones are more or less open, there being insufficient top soil to wash down and fill them. It is possible, therefore, to dig a good-sized hole with the hands simply by removing the loose rock. The trees are of Douglas fir, averaging about 14 inches in diameter, and having a crown density of 6 on a scale of 10. The large open rock slide to the west of the instrument shelter was selected for the rain gage because free from obstruction to the falling rain. The anemometer was also mounted in this open space. On account of the steep north slope this station receives practically no sunshine in the winter season. The instrumental equipment consists of one small louvred instrument shelter with its floor 7.5 feet above the ground, in which are installed maximum and minimum thermometers, a thermograph, and a hygrograph. Dry-and-wet bulb temperatures are taken with a hand-whirled psychrometer, the observer standing on the platform approach to the shelter. The anemometer is mounted on a wooden post and its cups are 4.9 feet above the ground. The anemometer is mounted in the customary vertical fashion, and since the wind on such a slope has a direction up or down the slope, we are really recording a modified component of its real velocity. The mouth of the raingage is 4.7 feet above the ground. An ordinary 8-inch overflow raingage is used. A snow bin, 5 feet by 5 feet was installed to the northeast of the shelter. This bin is used only for determining the depth of the newly fallen snow and is emptied at each observation. The snow caught in the 8-inch gage is used as the standard. The bulb of a telethermoscope buried 1 foot in the ground, just west of the instrument shelter, gives the soil temperature at that depth. The 4-foot temperature is obtained by a thermometer in a 1-inch iron pipe. Between the instrument shelter and the anemometer a board shanty, 6 feet by 8 feet, has been built for the convenience of the observer. It is low and so placed as not to interfere with the exposure of the instruments.

Station A–2.—Station A–2 is located 550 feet N. 80° W, of Dam A. Its elevation above sea level is 9,609 feet. The station is just across stream A from Station A–1, and horizontally distant but 406 feet. The slope is, however, entirely different, the angle being 34° 20′ toward S. 56° E. This station is exposed to the sun nearly all day. The soil is composed of earth and large rock fragments, the rocks weighing, say, 100 to 200 pounds, and being firmly embedded in the earth. Very little humus is found on the ground. The timber is Douglas fir, the trees being about 18 inches in diameter with a crown density of 5 on a scale of 10. The instruments are an 8-inch rain-gage and a maximum and a minimum thermometer, exposed in a small louvred shelter as at A–1. The floor of the shelter is 6.9 feet above the ground.

Station B–1.—Station B–1 is located 381 feet S. 30′ W. of Dam B and is 9,426 feet above sea level. The slope of the ground is 37° 30′ toward N. 24° E. The soil is mostly a sandy loam, with broken rock interspersed and with a good cover of fir needles. The station receives but little sunshine in winter: The instrument shelter is in the densest Douglas fir on the watersheds. The trees are not large, probably 6 inches average trunk, but they are close together, with a crown density of 9 on a scale of 10. This tract of fir is small in extent, and the timber changes abruptly at its western edge to aspen, with young fir coming on. In this aspen and young fir, which is dense and about 15 feet high, an open space was cleared for the rain-gage and anemometer. In clearing this space the rule that no object should be nearer to the raingage than its own height was observed as far as practicable. This cleared space is well protected from the wind. The change that takes place in the wind movement at this station after denuding ought to be a correct index of the effect of a forest on this factor. The snow bin is located at the extreme western edge of the cleared space. The floor of the instrument shelter is 7.3 feet above the ground, the mouth of the raingage 4.1 feet, and the anemometer cups 4.7 feet. The instrumental equipment consists of maximum and minimum thermometers, a thermograph, and a hygrograph, all in a small louvred shelter of the same pattern as on A; a rain gage of standard 8-inch overflow pattern; an anemometer mounted vertically; a snow bin 5 feet by 5 feet. A telethermoscope whose bulb is 1 foot in the ground just west of the instrument shelter was installed in January, 1912, for the purpose of observing soil temperatures. The iron pipe for 4-foot temperatures was installed in September, 1913. A shanty 6 by 8 feet was built for convenience and shelter.

Station D.—Station D is located near the top of the mountain, elevation 10,949 feet above sea level. This station is in the burned region, and hence the only timber consists of dead trees, standing and fallen. The ground in the vicinity of the station is practically level. The station is exposed to winds from all directions except the west, where it is slightly protected by rising ground. The soil is clay gravel, tough enough to make good mortar. The equipment consists of one small louvred instrument shelter whose floor is 6.9 feet above the ground, containing maximum and minimum thermometers and a thermograph; one 12-inch tipping-bucket raingage 4.9 feet above the ground, which is connected with a recorder at the C. station by aerial wire; one 8-inch overflow raingage 4.9 feet above the ground, and one snow bin are in close proximity to the shelter. Soil temperatures are obtained from thermometers in tubes, the shorter one being of wood. A log shanty has been built for the comfort and convenience of the observer. Telephonic communication is maintained with the office by the use of one of the rain-gage wires and a ground return.

Station C.—The C station was from the start equipped with a rather complete set of meteorological instruments as follows: Two standard barometers, a barograph, a triple register recording wind direction, velocity, sunshine, and rainfall. A standard Weather Bureau instrument shelter on galvanized-iron supports was installed on a grass-covered east slope, 400 feet north of the office building, and the raingage was placed 300 feet farther north in a stand of young aspen. The floor of the instrument shelter is 11.3 feet above ground, the wind vane is 16.9 feet, and the anemometer is 15.6 feet above ground.

Snow scales.—In order to determine the depth and density of the accumulated snowfall of winter, 32 permanent points of measurement were selected, 18 on A and 14 on B. At each point a permanent snow scale or stake 12 feet high was firmly set in the ground. Each scale represents a definite area and the scale reading is applied to the acreage of the area. The details of slope and exposure of the snow scales appears in Table 18, and the location may be seen by references to figure 17.

Personnel.—The following-named employees of the Forest Service were actively connected with the work of getting the experiment station under way, viz., Mr. Niles Hughel, who did the surveying, and Mr. Claude R. Tillotson, who rendered valuable assistance in a number of ways. Mr. Peter Keplinger served as observer and representative of the Forest Service during the early years of the work, and Messrs. Murdock, Flint, and Glendening of the Forest Service also served at the station.

On the part of the Weather Bureau, Mr. Benjamin C. Kadel planned and installed the equipment and apparatus for the meteorological observations, snow surveys, precise streamflow measurements, and determination of coefficient of stream discharge, and started the observational work in October, 1910. In all of this work he was ably assisted by Forest Service employees on duty at the station.

Following is a list of Weather Bureau officials who have served at this station.

Mr. Benjamin C. Kadel,[5] June, 1910, to August, 1912.
Mr. Harris A. Jones,[5] August, 1912, to February, 1914.
Mr. T. A. Blair,[5] March, 1916, to March, 1918.

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[5] In charge.

Mr. A. A. Justice,[5] February, 1916, to September, 1917.
Mr. J. H. Jarboe,[5] September, 1917, to October, 1918.
Mr. E. H. Jones,[5] October, 1918.
Mr. Julius C. Smith, August, 1912, to May, 1913.
Mr. B. R. Laskowski, June, 1913, to September, 1914.
Mr. M. M. Maguire, September, 1914, to October, 1916.
Mr. A. C. Wright, May, 1916, to September, 1917.
Mr. H. M. Howell, November, 1916, to May, 1917.
Mr. G. P. Murphy, September, 1917, to October, 1917.
Mr. E. H. Fletcher, October, 1918, to December, 1918.

THE PROGRAM OF OBSERVATIONS.

The program of meteorological and stream-flow observations as originally adopted was not materially changed during the first stage of the experiment. It involves daily observations, at 9 a. m., at Stations A–1, A–2, B–1, B–2, and C.

In the beginning the north-slope stations of the two watersheds were given the more complete instrumental equipment as follows: Maximum, minimum, dry and wet thermometers, a thermograph, a hygrograph, an anemometer, a standard 8-inch raingage, a 5-foot snow bin, and a 12-foot snow scale, the latter set permanently into the ground. Later in the experiment a shielded snow gage of the Marvin pattern was added at all of the meteorological stations. Thermometers for determining the soil temperature at depths of 12 and 48 inches were also added on north slopes in 1912. Weekly determinations of soil moisture at all watershed stations were made during the summer months of 1914 to 1919, both inclusive.

The equipment of the south-slope stations in the beginning was limited to maximum and minimum thermometers, a raingage, and a snow scale. On May 31, 1913, the thermometric readings were discontinued and a little later soil temperatures at 18 and 48 inches were begun. Precipitation was continuously recorded at south-slope stations throughout the experiment.

Finally, measurements of depth of snow on the ground *daily* were made at all primary watershed stations except D. Beginning with December of each year, a bimonthly measurement of the depth and density was made at each snow-scale on the watershed until near the beginning of the snow-melting season in the spring, when the measurements were made at three-day intervals in 1912 and 1913. Beginning with March, 1914, and continuing to date, the observations have been at five-day intervals during that period.

At the D station, by reason of its remoteness from the camp, the sheets of the automatic instruments were changed at 6-day intervals and eye readings for check purposes were made on the dates when the sheets were changed. The daily record of wind velocity and of rainfall in the summer were automatically registered in the office at the C station by electrical transmission line.

Stream-flow measurements.—The height of the water in the basins above the V-notch in the weirs was automatically recorded by a Friez water-stage recorder and the instrumental record was checked by the daily reading of a hook gage.

In July, 1911, the rectangular weirs were torn out and triangular weirs installed. The advantages of triangular weirs may be stated as follows: Perfect aeration of nappe; automatic accommodation to all stages, with particular advantage in the case of extremely low stage; an increased amplitude of oscillation of the water surface in the basin at low stage, with consequent increase in the accuracy of the measurements; the use of but one function, height, in the computations; and the elimination of the leading channels from the structural work. These leading channels are difficult to construct with uniform sides, while without them a difficult and doubtful correction for end contraction must be introduced. The weirs are simply steel plates 3 feet by 4 feet and 0.5 inch thick, out of which right-angled notches have been cut. The vertical depth of each notch is 1.5 feet, which gives a maximum capacity of 7 second-feet—seven times greater than the crest of the flood of October, 1911. The faces of the weirs are beveled off for a distance of 2 inches on the downstream side, with a crest width of one-sixteenth inch. The flow of water under gravity over a triangular weir of this form is given by the U. S. Geological Survey as 2.64 times the five-halves power of the head, the flow being expressed in cubic feet per second, and the head being the vertical height in feet of the still water in the pond above the vortex of the weir notch. The above formula is the same as derived by Prof. James Thompson, of Belfast, in the experiment with a triangular weir of a piece of thin sheet iron.

For the purpose of measuring the height of the water in the basin above the weir notch, a Boyden hook gage, an instrument familar to engineers, is used. The essential principle of the instrument is that the setting is effected by causing the point of a hook to approach the water surface from the *under* side. The method is so accurate that different observers never vary more than 0.001 foot from the same reading. The Boyden gage is secured to a concrete wall be means of bolts set in the concrete. For the purpose of stilling any waves that may be present, a piece of iron pipe, 6 inches in diameter, the top projecting about 6 inches above the water, is set under the hook gage. The pipe rests unevenly on the concrete bottom of the basin, and to provide further for the free access of water, a half-inch hole was drilled through the side of the pipe 6 inches from the lower end. For the purpose of setting the zero of the hook gage to the level of the weir notch, a special arrangement was devised. A section of iron pipe was embedded in a concrete base weighing some 10 pounds. Into the top of the pipe a wooden plug was driven. A screw hook was then straightened out and one end sharpened to a point. The screw hook was then screwed into the wooden block so that the length of the base pipe and hook was approximately the depth of the water in the basin about

[5] In charge.

FIG. 8. Dam A, showing cross-channel wall and wing wall extending upstream to ridge of clay.

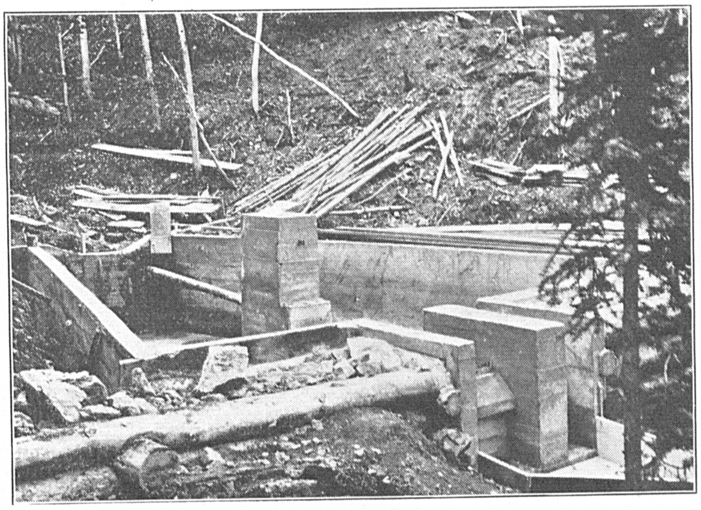

FIG. 10. Completed basin at Dam A with rectangular weirs, as seen from downstream end.

FIG. 9. Completed basin at Dam A from upstream end. Column in center—still well, later enlarged for 20-inch float.

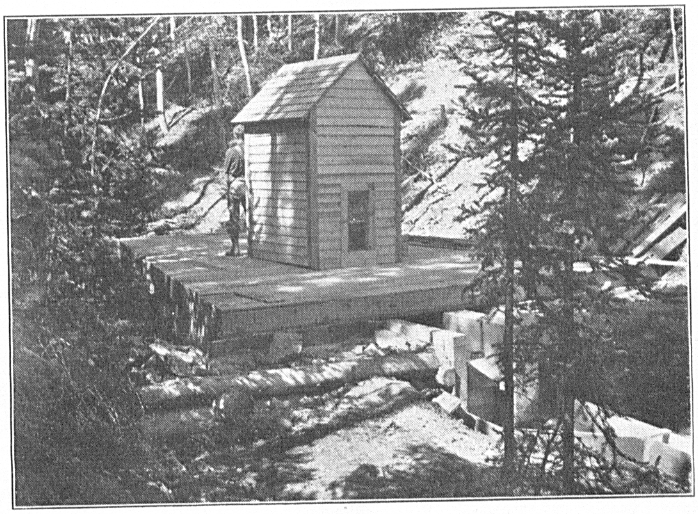

FIG. 11. Basin at Dam A covered with shelter house for register.

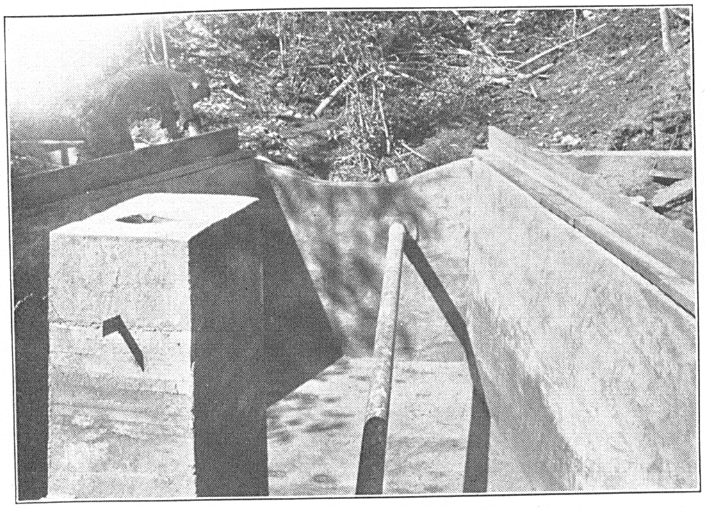

FIG. 12. Basin at Dam B just ready to cover.

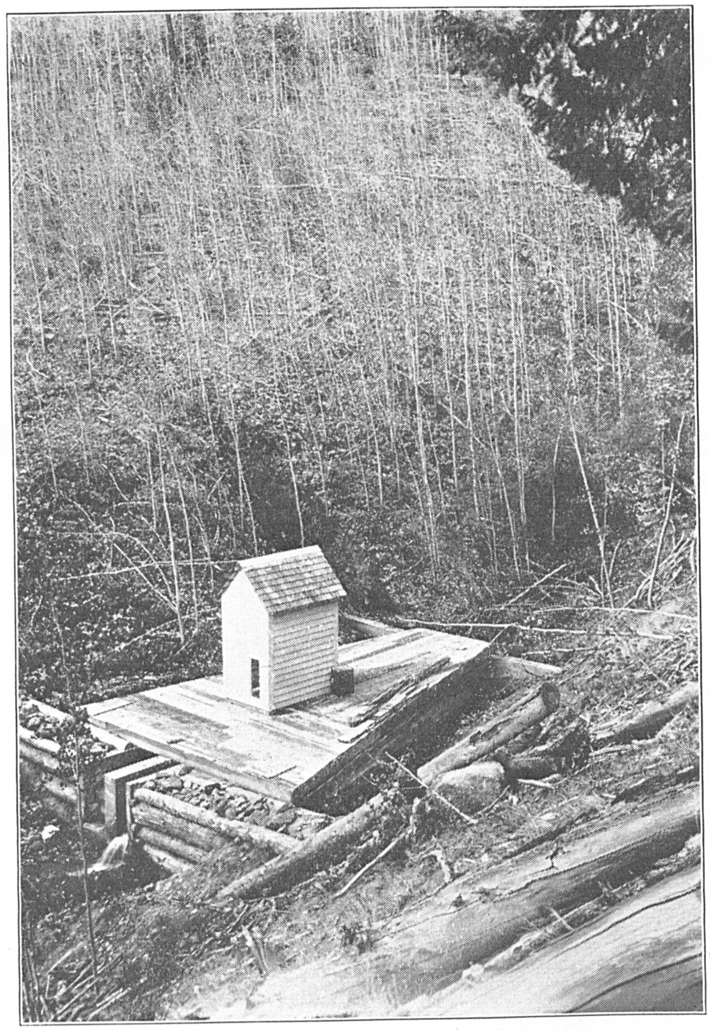

FIG. 13. Dam B, covered and ready for use.

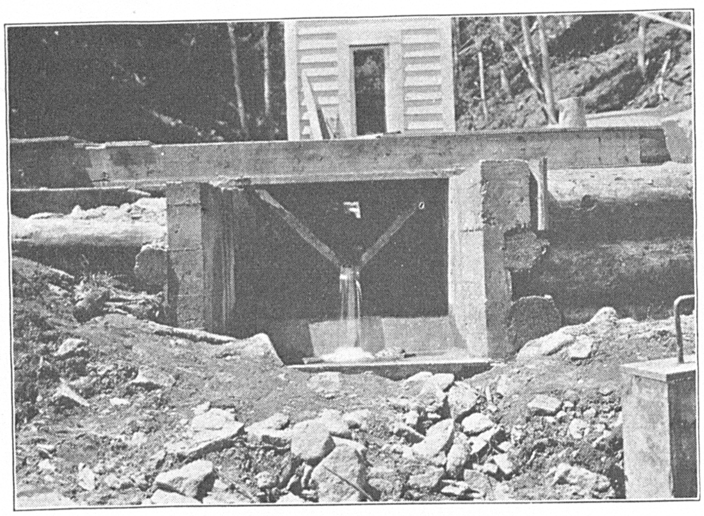

FIG. 14. Triangular weir which replaced rectangular weirs of 1911.

a foot back of the weir. The entire apparatus was then set into the basin just back of the weir. By means of a spirit level, one end of which is filed to fit into the weir notch, the point of the screw hook may be finally adjusted to the level of the weir notch. The water in the basin is then adjusted so that the screw hook just pierces the surface. The hook gage may then be set to its zero. The method is simple and accurate, and frequent examinations of the accuracy of the zero may be made without difficulty. Diagrams showing the general plan and details of construction of the dams will be

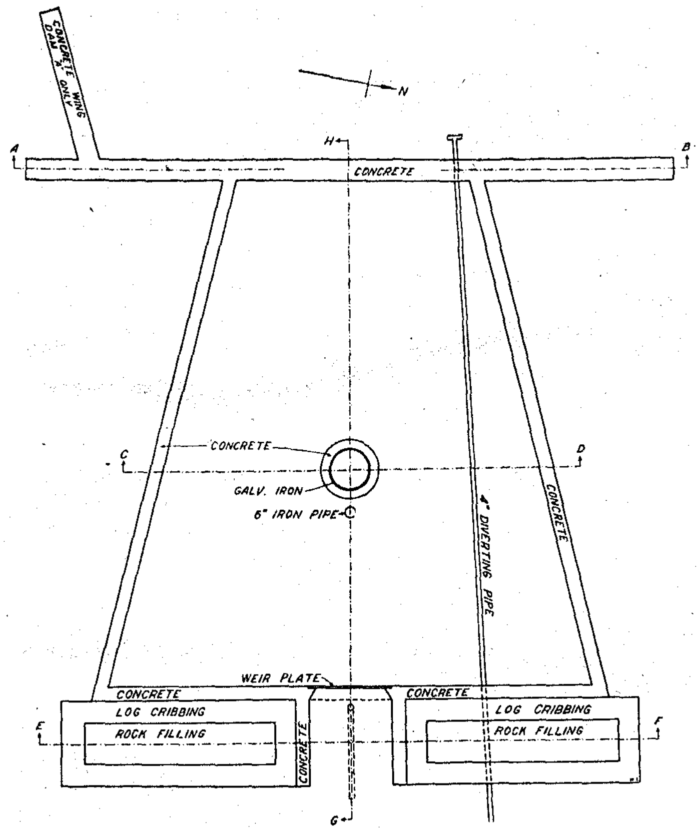

FIG. 6. General plan of dams.

found in figures 6 and 7, and halftone figures 8–14 further illustrate the methods of construction of the dams.

Discharge coefficients.—To obtain the high degree of accuracy required in the stream-flow investigation, it was thought best actually to determine the discharge coefficients rather than to accept the published values. This was particularly necessary because the weirs differ slightly from the Thompson weir in that they had to be made one-half inch thick to provide the necessary strength, while the Thompson weirs were of thin sheet iron. Furthermore, every weir must of necessity be subject to its own departures in construction from a theoretically perfect cutting of the angle, crest width, and level. Also, in placing the weir in position, the concrete may set unevenly, thus throwing the weir slightly out of plumb. For each dam, three tanks made of 16-gage galvanized iron, with iron hoop at the top rim, each tank 4 feet in diameter and 4 feet in depth, were mounted on a platform built far enough below the dam to give the required fall. Over the middle of the platform a galvanized-iron funnel, top 24-inch diameter, tube 6-inch diameter, was suspended in a gimbal or universal joint, so that the lower end of the funnel hung just above the tops of the tanks. The overflow from the weir is conveyed into this funnel through a V-shaped trough, lined with galvanized iron. The method of suspension of the funnel permits the water to be directed into either of the three tanks or into a wooden waste pipe, the change being effected in a fraction of a second. The areas of the tanks were determined by taking the circumferences at four heights in each tank with a steel tape, then computing the mean area for that portion of the tank used, allowance being made for the thickness of the iron. To eliminate the error due to irregularity of bottom the tanks were first filled to a depth of about 2 inches and

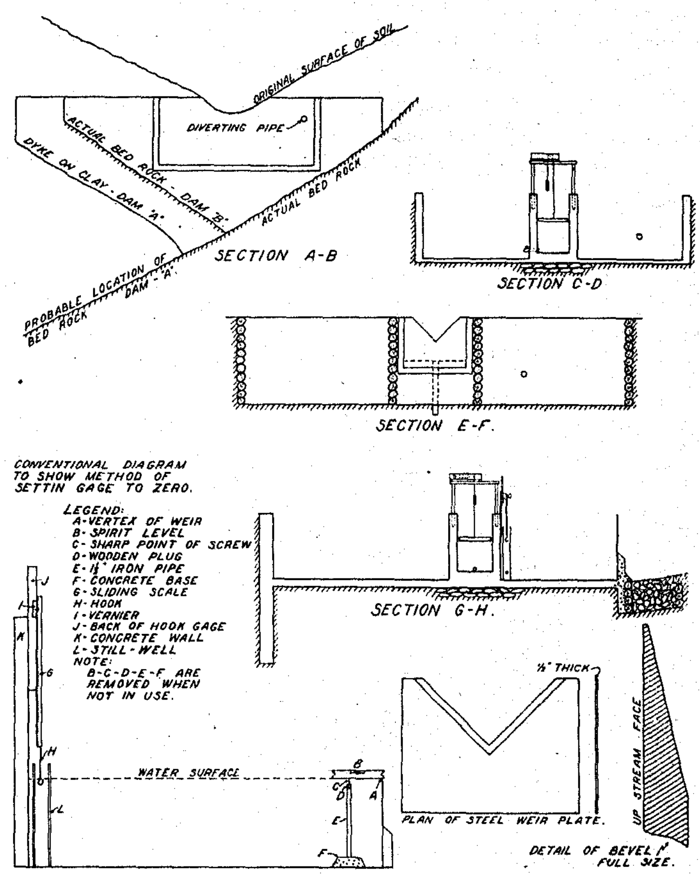

FIG. 7. Details of construction and measuring devices.

measurements of this height and of the height after the tank was filled were made by means of a hook gage, which was made by transcribing the graduations from a surveyor's rod. The time of beginning and ending a test was determined by use of an ordinary watch. Tests were made by two men, one man making continuous readings of the hook gage in the basin while the second man filled the tanks. Practically all of the tests were made at times of very little fluctuation in the head, and the mean of all hook-gage readings was used as the head. The detailed measurements and computations are too numerous to reproduce. Each individual entry represents a measurement of from 40 to 130 cubic feet of water, most tests having been made with the larger amounts. The only tests thrown out were a few that were unpardonably bad, the cause of the discrepancies being generally recognized and noted.

From these tests, of which several hundred were made at varying heads, rating tables, known as "preliminary tables," were constructed and used in determining the discharge from July 25, 1911, to April 30, 1912.

Subsequently all of the material used in constructing the preliminary tables, plus a few additional tests, was revised in the light of the new evidence and combined in tables known as the Kadel-Keplinger tables; and these tables, which did not differ materially from the preliminary tables, were used during the period May 1, 1912, to March 31, 1914, for A, and May 1, 1912, to August 31, 1913, for B. A second critical examination of all of the tests available up to the autumn of 1913 was made by Mr. C. G. Bates, of the Forest Service, in October, 1913, and rating tables were constructed (the Bates tables). These tables were put into use on B in September, 1913, and on A on April 1, 1914.

Table 5 shows the coefficients on which the several tables are based, for identical heads. These are the figures to be substituted for 2.640 in the U. S. G. S. formula for triangular weirs in general. The several tables are to be distinguished by the following letters: *P*, Preliminary tables; *K*, Kadel-Keplinger tables; *B*, Bates tables.

TABLE 5.

Head.	Coefficient (*P*).	Coefficient (*K*).	Coefficient (*B*).
0.300	2.660	2.622	2.639
0.400	2.620	2.590	2.606
0.500	2.580	2.573	2.585
0.600	....	2.564	2.571
0.700	....	2.561	2.563
0.800	....	2.557	2.558
0.900	....	2.554	2.553

CHAPTER II.

THE CLIMATE OF THE WAGON WHEEL GAP AREA.

The geographic location of the Wagon Wheel Gap area, remote from both oceans and in the midst of a rugged mountain area, imposes upon it a climate which partakes of the charactertistics both of mountain and continental climates. With this idea constantly in mind, the following climatic elements will be discussed in order: Temperature of air and soil, precipitation (rain and snow), humidity of the air, direction and velocity of the wind, sunshine, and cloudiness. The various statistics as compiled for the calendar months will be presented in the order in which the different elements are taken up in the text. Publication of the monthly or weekly statistics in extenso is deferred until the final report is made. The streamflow record has been made to begin after the date of the installation of triangular weirs, viz, in July, 1911. The meteorological record begins with November, 1910, although complete observations are not available until after July, 1911.

AIR TEMPERATURE.[1]

The discussion of temperature is based on daily systematic observations of standard thermometers exposed in the regulation thermometer shelter at the north-slope stations of both watersheds for a period of eight years, 1911 to 1918, inclusive. Daily thermometric observations are also available for the south-slope stations on both watersheds from November, 1910, to May, 1913, a period of 31 months. Thermographs were maintained at north-slope stations and also at the D station for the entire eight-year period and at the G station for the four years, 1914 to 1917. The monthly means as deduced from hourly readings of the thermographs, checked by daily comparisons with the mercurial thermometers in the case of A and B, and weekly comparisons in the case of the D and G stations, are given in Table 6.

TABLE 6.—*Monthly mean temperature, north-slope stations of watersheds A and B, Wagon Wheel Gap experiment stations, 1911 to 1918, inclusive, except for the G station, which is based on the four years, 1914 to 1917.* (*From hourly readings.*)

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
A[2]......	15.6	17.7	24.3	32.4	41.3	51.1	53.6	51.8	45.5	35.9	24.8	14.7
B[2]......	14.9	17.3	24.0	32.5	41.5	51.2	53.8	51.8	45.3	35.8	24.3	13.9
D........	15.6	17.0	21.2	27.7	36.3	47.5	50.2	49.0	43.0	33.6	24.7	15.1
G........	12.7	15.8	18.9	26.8	32.6	45.4	49.1	47.0	41.8	32.8	25.2	14.5

[1] Degrees Fahrenheit and English units are used throughout this discussion.
[2] North slope.

Considering the north-slope stations as representative of the watersheds, it is at once apparent that the mean temperature of the two watersheds is practically the same. The differences range from 0.8° in December to 0° in August. A is uniformly higher than B, except in the months April to July, inclusive, when it is a small fraction of a degree cooler on the average than B.

These small differences in the mean are derived, of course, from larger differences in the individual readings; it is interesting to note that they are most pronounced in the daily maximum temperatures and for the season close to the equinoxes; they may therefore have a purely astronomical origin, viz, in the different angle of incidence of the sun's rays on the lower portion of A as compared with B. The azimuth of A slope at station A–1 is north 24 degrees west, while that of B is north 24 degrees east. As noon approaches in the latitude of Wagon Wheel Gap, in March for example, the sun will be moving not upward along the prime vertical, but obliquely toward the south-southwest. After reaching the meridian its course will be obliquely toward the north-northwest, in which position its rays will fall upon portions of the slopes of A at a higher angle than on B.

The D station, at an elevation of 1,355 feet higher than A–1, and 1,530 feet higher than B–1, has practically the same winter mean temperature as the lower stations, a spring temperature 4° lower, summer about 3° lower, and autumn 1.5° lower. The winter minimum temperatures of the D station are considerably higher than those of the lower levels; hence the equality in the winter means. The G station is 624 feet higher than D, on a ridge between two small streams and about 500 feet below the highest part of the ridge. It is colder than D in all months of the year, more so in winter than in summer. It is included in Table 6 merely to complete the record.

Advance of the season.—The character of the season as indicated by the rate of increase in the monthly mean temperature from March to May, inclusive, is shown by the figures in Table 7. Some seasons are considerably in advance of others in the matter of the normal increase of temperature with the advance of the season. The average increase in monthly mean temperature, March to May, inclusive, is 26.8°, but this increase may come early, as in 1913, or late, as in 1918, and in some seasons the average increase may not be realized. (See in this connection Prof. Marvin's discussion of the Annual March of Temperature, on subsequent pages.)

TABLE 7.—*Increase in monthly mean temperature.*

In °F.

Year.	March to April.	April to May.	May to June.	Total.	Remarks.
1911	6.5	9.0	7.9	23.4	
1912	5.2	12.9	6.5	24.6	
1913	12.1	10.5	4.8	27.4	A cold April.
1914	8.4	9.0	8.4	25.8	
1915	13.3	3.1	12.1	28.5	
1916	5.3	8.1	11.0	24.4	
1917	11.3	6.2	15.7	33.2	
1918	3.4	11.6	12.3	27.3	

South slopes.—The south slope of each watershed is somewhat warmer than the north slope, but the excess in the monthly means is generally less than a whole degree, except that for the cold months, November to March, it may amount to as much as 2° or 3°. The excess in monthly means, south over north slope, is as follows:

	November.	December.	January.	February.	March.
A	2.1	1.8	1.8	1.6	0.6
B	2.5	3.0	2.7	2.6	1.8

This comparison is based upon monthly means that have been derived from the daily extremes instead of the 24-hourly readings as in Table 6. A series of corrections to reduce the means derived from the daily extremes to the true daily means shows that for watershed A the mean temperature, maximum and minimum, divided by 2, gives results that are in excess of the true daily means by amounts varying from 0 in February to 2.1° in August. In general, the corrections for the summer months in both watersheds are the greatest. In the B watersheds small positive and negative corrections offset each other in the mean, with the result that in three months of the year the correction is zero. In the A watershed positive corrections were rarely found in the individual months and not at all in the final means. Further analysis of the excess in monthly mean temperature as above shows that this excess is due to higher maxima on the south slopes of the respective watersheds; thus:

	Excess of maxima on south over north slope (31 months' observations), means for—				
	November.	December.	January.	February.	March.
Watershed A	3.6	3.3	3.4	2.7	0.8
Watershed B	5.3	4.9	5.0	4.4	3.3

The mean minima for the identical periods and slopes are slightly higher for the south than for the north slopes, although the greatest excess for any month does not equal 1°. If we go still farther and make an intercomparison between corresponding slopes of the two watersheds we find that the mean temperature, regardless of how obtained, is substantially the same. As illustrating this feature, the monthly means of the daily extremes for the eight full years at the north-slope stations is presented in Table 8.

TABLE 8.—*Monthly means of the daily maxima and daily minima.*

WATERSHED A.

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
Max	25.3	28.4	36.4	44.6	54.3	66.6	68.6	67.0	59.7	47.7	36.1	24.2	46.6
Min	6.2	7.7	13.7	22.0	29.7	37.5	42.8	40.8	34.6	26.1	15.2	5.8	23.5

WATERSHED B.

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
Max	24.4	27.8	34.9	43.1	53.3	65.6	67.6	65.6	57.9	47.1	35.3	23.3	45.5
Min	5.6	7.2	13.5	21.8	29.3	36.9	42.3	40.3	34.1	26.0	14.7	5.1	23.1

D (UPPER PART WATERSHED A).

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
Max	24.9	27.0	31.7	37.3	45.9	58.0	60.7	60.0	53.7	43.8	35.4	24.6	41.9
Min	7.5	8.9	12.3	18.9	27.1	37.8	41.8	40.3	34.4	25.1	16.2	7.4	23.1

While the means in Table 8 show that the north slope of A is slightly warmer (1.1° on the mean of the year) than the corresponding slope of B, the observations made on the south slopes of the two watersheds show that both the daily maxima and the daily minima of the south slope of B are higher by a small amount, not to exceed 2° in the mean, than on the corresponding slope of watershed A.

Monthly extremes of temperature.—An examination of the monthly extremes of temperature at stations A–1, B–1, and D brings out the following points:

The absolute range in temperature for the eight-year period, January, 1911, to December, 1918, inclusive, was 106° for Station A–1, or from 24° below zero to 82° above; for Station B–1, 105°, or from −25° to 80°; and for station D, 94°, from −22° to 72°.

The highest temperature ever recorded during the period of observation at A–1 was 82°, on June 10, 1918, and July 4, 1916, and the lowest, −24°, on February 1, 1916; at B–1 the highest temperature ever recorded was 80° on June 11, 1918, and the lowest −25° on February 1, 1916; and at Station D, the highest temperature ever recorded was 72° on June 11, 1918, and July 5, 1913, and the lowest −22° on January 2, 1919.

The extreme temperatures for each month and year are included in Table 9.

TABLE 9.—*Absolute maximum and absolute minimum temperatures.*

ABSOLUTE MAXIMUM.

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
A–1	46	43	54	60	70	82	82	77	71	67	53	45	82
B–1	45	41	52	58	69	80	79	76	69	66	53	44	80
D	50	43	49	55	62	72	72	71	65	63	54	47	72

ABSOLUTE MINIMUM.

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
A–1	−21	−24	−8	1	10	22	31	33	17	5	−11	−16	−24
B–1	−21	−25	−10	0	11	22	30	32	18	5	−11	−17	−25
D	−22	−21	−8	−1	4	19	29	32	15	−1	−13	−18	−22

This tabulation shows that during the winter period, November to February, inclusive, the absolute maximum at the higher elevation, D, is generally *above* the maxima at the lower stations, and, during the same period, the absolute minimum at the higher station is occasionally not so low as the minima at the lower elevations.

These results, while somewhat at variance with the ordinary view of the law of temperature change with altitude, are nevertheless quite in accord with the later views upon the temperature conditions which prevail in the free air at neighboring mountain and slope stations. The D station is located in a burned-over region and is not protected by the shade of the timber; it is subject to unobstructed insolation at all times of the year. It is probable that these facts, together with the greater opportunity for warming by reflected heat from the snow cover and dead timber, will account for the higher maxima observed in the cold season.

As elsewhere stated, there is more opportunity for air mixing due to wind movement at the D station than at the slope stations at lower levels, consequently higher minima. There is another type of temperature inversion that occasionally appears in mid-winter, viz, a decided rise of temperature at the upper stations which does not appear at the lower stations; an example is given in Table 10.

TABLE 10.—*Temperature inversion, Wagon Wheel Gap, Colorado, February 10, 1918.*

Station.	Elevation.	Temperature, °F.		
		Mean.	Maximum.	Minimum.
River Valley	8,437	6.1	30	−13
A-1	9,601	17.5	34	4
D	10,956	25.0	41	14

The rate of decrease of temperature with increase of elevation in this example is about 1° F in 100 feet. Inversions of this character appear to occur in connection with a certain well-defined type of pressure distribution over Colorado. They are not material in this discussion.

Mean daily range of temperature.—The mean daily range of temperature at the two north-slope stations is practically the same. averaging about 22° on the mean of the year. It is about 4° less at the more elevated stations, D and G, and is greatest on the south slopes of both watersheds. The south slope of watershed A has a greater daily range than the north slope, but the excess is not so pronounced as for watershed B.

Diurnal variation.—The diurnal variation of temperature at the Wagon Wheel Gap stations is largely a matter of academic interest. It has been calculated for the A–1 and the D stations.

The amplitude of the variation at the upper station is considerably less than at the lower station and the hour of occurrence of the maximum and the minimum temperatures at the upper station is earlier in the day than at the lower station; for example, the hour of maximum in winter at D falls at 1:00 p. m., whereas at A it occurs 2 hours later. The D station is probably less affected by surface conditions of slope and surface cover than the A–1 station and reacts to atmospheric process much as would a point in the free air.

Variations from the mean.—Eight years, of course, is too short a period within which to expect anything like the full swing of the means from one extreme to the other, but the small range in the monthly means was unexpected. The average excess above the mean is 4° and the average deficiency 3.2°. The greatest deficiency was 6.3° in March. In the snow-melting season, March to May, the greatest excess was 4.6° in March, 1916, and the greatest deficiency occurred in March, 1917. In general it would appear that the variation from the mean at elevated stations is less than on the lowlands. Comparing the variations from the mean for Longs Peak, Larimer County, altitude above sea level 8,600 feet, with those for Wagon Wheel Gap, shows very substantial agreement between the two stations.

Prof. C. F. Marvin has kindly contributed a discussion of the annual march of the mean temperature at Wagon Wheel Gap, as follows:

ANNUAL MARCH OF MEAN TEMPERATURE.

Wagon Wheel Gap, Colo., Station A.

By Prof. C. F. MARVIN.

This discussion is based on a harmonic analysis of the values of the weekly mean temperature computed from values of the means of the daily maximum and minimum. The period covers the observations from July 2, 1911, to July 2, 1919. The extra day over 52 weeks in a year has been included in the week designated by the central date, July 12, which week contains 8 instead of 7 days, viz, July 9 to 16, inclusive. February 29 on leap years was similarly included in the week designated March 1, viz, February 26 to March 4, inclusive.

While observations of hourly values are available, a correction to reduce the mean of the maximum and minimum to the mean of the 24-hourly values has not been computed or applied for this relatively short period.

As a matter of convenience or mathematical advantage, the annual cycle was chosen to begin with July 2, partly because the observations were thoroughly established and homogenous after this date, but chiefly because this date is near the period of the summer-time maximum and nearly stationary temperatures. The somewhat uncertain correction which the mathematical theory requires be applied to adjust the data to a perfectly closed cycle is then more likely to be small than if the year begins amidst the great fluctuations which mark the mid-winter season. In the present case the cycle fails to close by only 0.89, that is, the eight-year weekly mean for the first week of the cycle should be identical with the eight-year mean for the fifty-third week. The latter is 0.89 too high, but an adjustment for this small discrepancy is deemed unnecessary.

A harmonic analysis of long records for a considerable number o stations widely distributed over the United States shows conclusively that the annual march of temperature over large sections, especially in the Northeast, is remarkably well represented by a single fundamenta sine curve. Elsewhere such a fundamental and a harmonic of the second order suffice to fit the data in a highly satisfactory manner.

The same thing is found to be true in the case of the Wagon Wheel Gap data, even for the short period of eight years. A least-square analysis of the weekly mean temperatures gives the following harmonic equation of the second order:

$$(t = 34°.85 + 20°.94 \cos(\theta - 14°\ 55.'1) - 1°.20 \cos(2\theta + 67°\ 51.'7)$$

This is remarkably like the corresponding equation for Denver from the record of 45 years from 1872 to 1916, and closely resembles the curve for Omaha for the same period. Of course, the mean annual temperatures as given in the constant term of the equations differ, and, as to be expected, the extreme range as represented by the coefficients of the cosine terms is smaller at Wagon Wheel Gap on account of its high altitude. The dates for the summer maximum and the winter minimum are identical to a day at the two stations, Denver and Wagon Wheel Gap, namely between July 26 and 27 and between January 12 and 13.

GENERALIZATIONS.

Figure 15 shows the sweep of the annual curve and how the smooth mathematical line threads its way through the irregular march of the observed weekly means. Across the middle portion of the figure is shown without distortion the same irregular march of the weekly means. The residuals or departures in this case are calculated and plotted with reference to the *main fundamental wave* represented by the horizontal axis. There is also depicted by itself the second harmonic, the small amplitude of which (1°.20), as compared with that of the major wave, is noteworthy. The absence in the residuals of any conspicuous periodicity running through the whole year other than the second harmonic is the most striking feature of the data, and it is obvious a Fourier series can represent the residuals only when a large number of terms are employed. Any idea that such higher harmonics have a real existence in such a case or that any physical significance can be attached to them, is extremely difficult to prove.

Scanning the trace of residuals through the year, we note that for the eight years of these records quite normal conditions prevailed from July to the middle of October when a period of higher temperatures set in—crests *a*, *c*, with the cool wave *b* between them.

December, including the first week of January, is marked by protracted cold weather, *d*, *e*, followed in turn by alternating crests of notably warm and cool spells, *f*, *g*, *h*, extending to the second week of April when alternating crests *i*, *j*, *k*, *l*, of cool weather mark the balance of the month extending through May to the middle of June, when the year closes with a marked crest, *m*, of warm weather of nearly three weeks duration. One can not critically examine these warm and cool crests in conjunction with the detailed annual records without being much impressed with how greatly the distinguishing features depend for their presence in the record upon a single or a few conspiring abnormalities of a particular week or a single year. The deep crests of cold in December and warm peaks of January and February are largely due to exceptional weeks or years of extremes of this character which impress features upon the record which are gradually effaced only in a very long record. Without attempting to give here the reasoning, it is easy to show that as the length of the record increases the amplitude of the conspicuous crests grows smaller and smaller, seeming to indicate a tendency of the means of long series of observations to approach closer and closer to some such line as that given by the equation.

We may even expect the amplitude of the second harmonic to diminish or become inconsequental in some cases, but hardly in this section of the country. The second harmonic with an amplitude of 1.69° is clearly defined in the 45-year record at Denver and also at Omaha

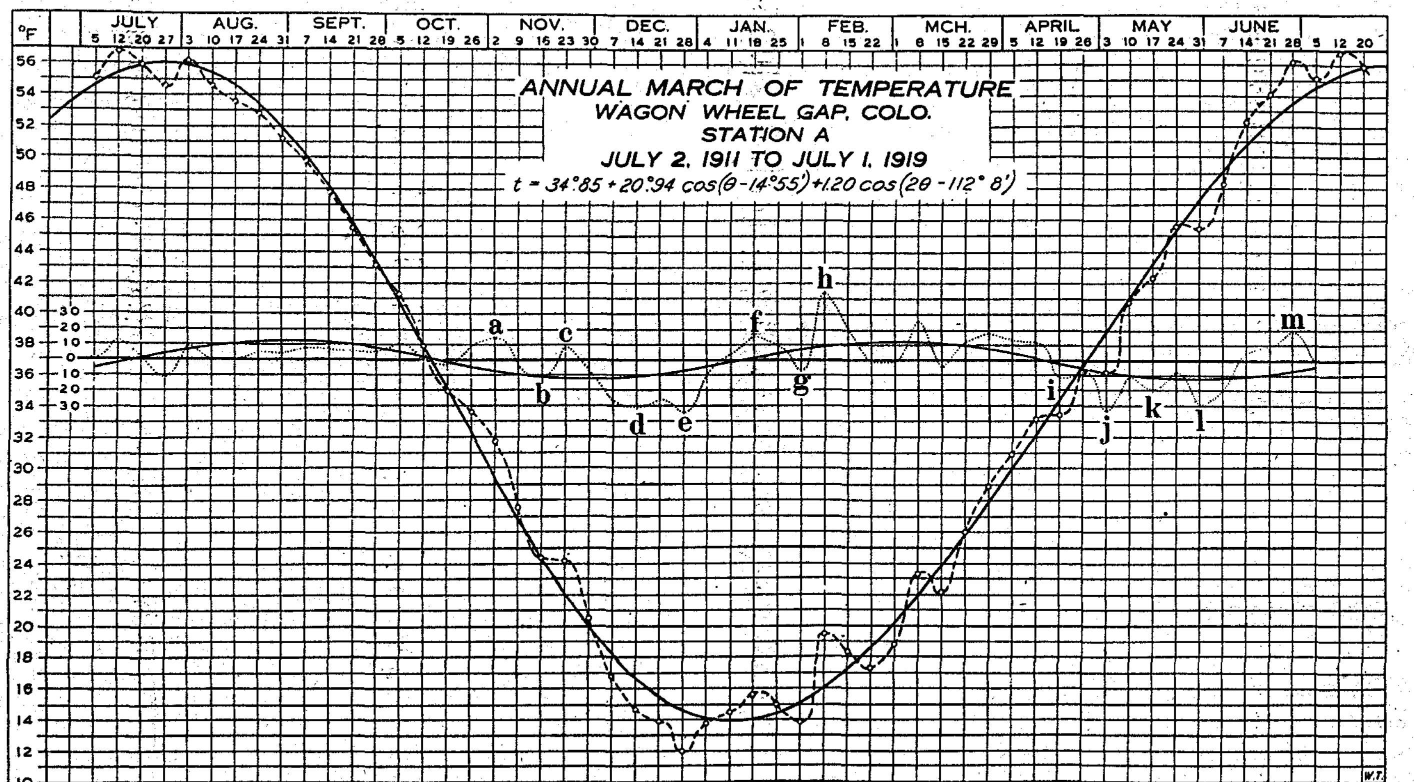

FIG. 15. Annual march of temperature at Wagon Wheel Gap.

with an amplitude of 1.87°, and evidence is distinctly wanting in these cases also of the presence of particular harmonics of higher order. It is fully recognized, of course, that the residuals can all be reduced to zero simply by computing additional terms of the Fourier series up to the possible maximum of 25 harmonics. The important point to grasp, however, is that the Fourier series as applied to the annual march of temperature converges with extreme rapidity, so that two terms only, sometimes one, entirely suffice. After that it is not a question of convergence, but simply a gradual closer approximation permitted by each addition of new constants to the equation.

The representation and the equation presented in the foregoing dealing with the normal weekly temperature at Wagon Wheel Gap station and the daily normals easily derived therefrom, as also the discussion of conspicuous features of the departures, are presented with great confidence, and any method of discussing such data without the use of an appropriate mathematical curve, such as plotting the data and drawing smooth free-hand curves, must be considered very unsatisfactory in comparison. To appreciate the power and superiority of the mathematics to analyze such data it must be recognized that the record comprises nearly 3,000 days of observation. The calculated temperature for any given week, for example, does not depend alone upon the paltry number of 56 single observations which make up the observed value of the eight-year weekly mean of this value modified partly by a regard for the observed values for adjacent weeks. In fact, every other value throughout the year has its influence upon any one according to its place. Each single calculated value has the full and partial weight and influence of many hundreds of observations back of it, a result otherwise unattainable without centuries of observations. The numerical data follow:

TABLE 11.—*Weekly mean temperature, Station A, Wagon Wheel Gap, Colorado.*

SUMS—DATA ARRANGED FOR CALCULATION OF HARMONIC COEFFICIENTS.

[Period of record, July 2, 1911, to July 1, 1919.]

r	I	II	III	IV	a	a'	b
0	55.1	13.7	....	....	68.8	41.4	68.8
1	56.8	12.0	14.5	56.2	139.5	86.5	− 19
2	55.9	13.9	15.6	54.1	139.5	80.5	+ 1
3	54.6	14.7	15.0	52.3	136.6	77.2	+ 20
4	56.2	16.8	13.8	48.3	135.1	73.9	+ 109
5	54.6	20.5	19.5	45.5	140.1	60.1	+ 101
6	53.6	24.2	18.3	45.6	141.7	56.7	+ 139
7	52.8	24.4	17.3	42.3	136.8	53.4	+ 176
8	51.2	27.5	18.8	40.8	138.3	45.7	+ 191
9	49.8	31.7	23.3	36.2	141.0	31.0	+ 220
10	47.8	33.6	22.2	36.2	139.8	28.2	+ 230
11	45.5	34.9	26.0	33.4	139.8	18.0	+ 210
12	43.2	37.9	28.9	33.1	143.1	9.5	+ 191
13	41.3	....	....	30.9	72.2	72.2	+ 104
Sums	718.4	305.8	233.2	554.9	1,812.3	734.3	+2,361

CALCULATED VALUES, FIRST HARMONIC.

r	b'	$a' \cos \theta_r$	$b \sin \theta_r$	$A_1 \cos \theta_r$	$B_1 \sin \theta_r$	Sum.	Diff.
0	41.4	41.4	....	20.24	....	20.24	....
1	+ 31	85.9	−.2	20.09	0.65	20.74	19.44
2	+ 35	78.2	+.0	19.65	1.29	20.94	18.36
3	+ 26	72.2	.7	18.92	1.91	20.83	17.01
4	+ 49	65.4	5.1	17.92	2.51	20.43	15.41
5	+ 81	49.5	5.7	16.66	3.06	19.72	13.60
6	+ 21	42.4	9.2	15.15	3.58	18.73	11.57
7	+ 34	35.4	13.2	13.42	4.04	17.46	9.38
8	+ 17	26.0	15.7	11.50	4.44	15.94	7.06
9	+ 52	14.4	19.5	9.40	4.77	14.17	4.63
10	+ 2	10.0	21.5	7.18	5.04	12.22	2.14
11	+ 32	4.3	20.4	4.84	5.24	10.08	− .40
12	+ 11	1.1	19.0	2.44	5.35	7.79	−2.91
13	+104	....	10.4	....	5.39	5.39	....
Sums	+909	526.2	140.2	....	....	....	....

$A_0=\frac{\Sigma a}{52}=34.85$

$A_1=\frac{\Sigma a' \cos\theta_r}{26}=20.238$

$B_1=\frac{\Sigma b \sin\theta_r}{26}=5.392$

$\tan\varphi=\frac{B_1}{A_1}$ $\varphi=14°\ 55'.1'$ 15.14 days after July 5

$a_1=\sqrt{A_1^2+B_1^2}=20.94$

SECOND HARMONIC.

Δa	$\Delta a \cos 2\theta$	$\Sigma b'$	$\Sigma b'. \sin 2\theta$
−3.4	− 3.4	51.8	+ 0.0
−3.6	− 3.5	4.2	+ 1.0
−0.3	− 0.3	6.7	+ 3.1
−3.2	− 2.4	2.8	+ 1.9
−5.9	− 3.4	10.1	+ 8.3
+1.8	+ .6	9.8	+ 9.2
+4.9	+ .6	5.5	+ 5.5
	−11.8	....	+29.0

$A_2=-\frac{11.8}{26}=-.4538$

$B_2=-\frac{29.0}{26}=+1.1154$

$\varphi_2'=-67°\ 51.7'$

$a_2'=-1.204$

$Y''=0$ at $\theta=11°\ 4.2'=11.23$ days$=1.6$ weeks

y' Max. at $\theta=56°\ 4.2'=56.89$ days$=8.13$ weeks

CALCULATED VALUES, SECOND HARMONIC.

r	$A_2 \cos 2\theta$	$B_2 \sin 2\theta$	Sum.
0	−0.45	....	−0.45
1	− .44	+0.27	− .17
2	− .40	+ .52	+ .12
3	− .34	+ .74	+ .40
4	− .26	+ .92	+ .66
5	− .16	+1.04	+ .88
6	− .05	+1.11	+1.06
7	+ .05	+1.11	+1.16
8	+ .16	+1.04	+1.20
9	+ .26	+ .92	+1.18
10	+ .34	+ .74	+1.08
11	+ .40	+ .52	+ .92
12	+ .44	+ .27	+ .71
13	+ .45	....	+ .45

TABLE 12.—*Weekly mean temperature, Station A, Wagon Wheel Gap, Colorado.*

OBSERVED AND CALCULATED VALUES WITH RESIDUALS.

[Period of record July 2, 1911, to July 1, 1919.]

Date.	x	y obs'd.	y' calc.	Cor. $y-y'$	2d harmonic.	Y'' calc.
July 5	0	55.1	55.1	0.0	−0.45	54.64
12	1	56.8	55.6	+1.2	− .17	55.42
20	2	55.9	55.8	+ .1	+ .12	55.91
27	3	54.6	55.7	−1.1	+ .40	56.08
Aug. 3	4	56.2	55.3	+ .9	+ .66	55.94
10	5	54.6	54.6	± .0	+ .88	55.45
17	6	53.6	53.6	± .0	+1.06	54.64
24	7	52.8	52.3	+ .5	+1.16	53.47
31	8	51.2	50.8	+ .4	+1.20	51.99
Sept. 7	9	49.8	49.0	+ .8	+1.18	50.20
14	10	47.8	47.1	+ .7	+1.08	48.15
21	11	45.5	44.9	+ .6	+ .92	45.85
28	12	43.2	42.6	+ .6	+ .71	43.35
Oct. 5	13	41.3	40.2	+1.1	+ .45	40.69
12	14	37.9	37.8	+ .1	+ .17	37.93
19	15	34.9	35.2	− .3	− .12	35.13
26	16	33.6	32.7	+ .9	− .40	32.31
Nov. 2	17	31.7	30.2	+1.5	− .66	29.56
9	18	27.5	27.8	− .3	− .88	26.91
16	19	24.4	25.5	−1.1	−1.06	24.41
23	20	24.2	23.3	+ .9	−1.16	22.12
30	21	20.5	21.2	− .7	−1.20	20.05
Dec. 7	22	16.8	19.4	−2.6	−1.18	18.26
14	23	14.7	17.8	−3.1	−1.08	16.76
21	24	13.9	16.5	−2.6	− .92	15.57
28	25	12.0	15.4	−3.4	− .71	14.70
Jan. 4	26	13.7	14.6	− .9	− .45	14.16
11	27	14.5	14.1	+ .4	− .17	13.94
18	28	15.6	13.9	+1.6	+ .12	14.03
25	29	15.0	14.0	+1.0	+ .40	14.42
Feb. 1	30	13.8	14.4	− .6	+ .66	15.08
8	31	19.5	15.1	+4.4	+ .88	16.01
15	32	18.3	16.1	+2.2	+1.06	17.18
22	33	17.3	17.4	− .1	+1.16	18.55
Mar. 1	34	18.8	18.9	− .1	+1.20	20.11
8	35	23.3	20.7	+2.6	+1.18	21.86
15	36	22.2	22.6	− .4	+1.08	23.71
22	37	26.0	24.8	+1.2	+ .92	25.69
29	38	28.9	27.1	+1.8	+ .71	27.77
Apr. 5	39	30.9	29.5	+1.4	+ .45	29.91
12	40	33.1	31.9	+1.2	+ .17	32.11
19	41	33.4	34.5	−1.1	− .12	34.33
26	42	36.2	37.0	− .8	− .40	36.59
May 3	43	36.2	39.5	−3.3	− .66	38.82
10	44	40.8	41.9	−1.1	− .88	41.03
17	45	42.3	44.2	−1.9	−1.06	43.17
24	46	45.6	46.4	− .8	−1.16	45.26
31	47	45.5	48.4	−2.9	−1.20	47.25
June 7	48	48.3	50.3	−2.0	−1.18	49.08
14	49	52.3	51.9	+ .4	−1.08	50.78
21	50	54.1	53.2	+ .9	− .92	52.29
28	51	56.2	54.3	+1.9	− .71	53.58

Calculation fixes the annual
Maximum at $\theta=21°\ 7'$
Annual minimum at $\theta=188°\ 20'$
viz, July 5+21.43 days=July 26.43.
and Jan. 11+ 1.60 days=Jan. 12.60.

To prevent any confusion that may arise from a purely verbal description of the temperature of the two watersheds, a table of comparative monthly means has been prepared and is presented as Table 13.

TABLE 13.—*Comparative mean temperatures.*

MONTHLY MEANS FROM 24-HOUR READINGS.

Stations.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
A_1 minus B_1.	+0.7	+0.4	+0.3	−0.1	−0.2	−0.2	−0.1	0.0	+0.3	+0.1	+0.5	+0.8	+0.2
A_2 minus B_2.	−0.4	−0.4	−0.4	−0.6	−0.4	0.0	+0.2	0.0	−0.1	−0.6	+0.2	+0.2	−0.2

MONTHLY MEAN MAXIMUM.

Stations.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
A_1 minus B_1.	+0.9	+0.5	+1.5	+1.5	+1.0	+1.0	+1.0	+1.4	+1.8	+0.6	+0.9	+0.9	+1.1
A_2 minus B_2.	−0.7	−1.4	−1.2	−1.4	−1.3	−0.9	−0.7	−1.4	−1.3	−1.6	−0.4	−0.6	−1.1

MONTHLY MEAN MINIMUM.

Stations.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
A_1 minus B_1.	+0.6	+0.5	+0.2	+0.2	+0.3	+0.6	+0.5	+0.5	+0.5	+0.1	+0.5	+0.7	+0.4
A_2 minus B_2.	+0.7	+0.5	+0.3	+0.2	+0.6	+1.1	+0.8	+0.4	+1.1	+0.3	+0.9	+0 9	+0.8

A–1 and B–1 are north slope stations; A–2 and B–2 are south slope stations.

The mean maximum temperature of A (north slope) is higher by 1.1° on the average of the year than that of B and the mean minimum of A is higher throughout the year than B by amounts ranging from 0.1° to 1.1°.

South slope temperatures.—It is quite evident that, while the mean maximum temperatures of the south slope of A, as represented by station A–2, are lower than for the corresponding slope of B, the mean minimum temperatures of B are about the same amount higher, thus offsetting the effect of the lower maxima on A. It is obvious that the amount of solar energy received on each unit of surface in the south slopes is greater than on north slopes because the sun's rays are very nearly perpendicular at certain hours of the day. Since, however, only a small part of the solar energy is absorbed by the atmosphere, we should expect little effect upon air temperature as compared with soil temperature. The greatest effect of south slope insolation may be looked for in snow melting around and near objects which reflect the solar rays or absorb and reradiate them.

Prof. Kimball has computed the amount of solar radiation in gram-calories (amount of heat required to raise the temperature of a gram of water 1° C.) for each of the north and south slope stations on both watersheds. The results are given in Table 14. This table shows that while the total radiation per unit of surface which falls upon the two south-slope stations is practically the same, the amount which falls upon the two north-slope stations is slightly different at different seasons. For the vernal equinox—the time of snow-melting—solar radiation becomes effective on north slope of B a little earlier in the morning than on A, but, on the other hand, the intensity of radiation on the north slope of A reaches a higher value than on B. The maximum on A is 0.61 gram-calorie per minute at 2 p. m., whereas the maximum on north slope of B is but 0.46 gram-calorie per minute at 11 a. m. A is constantly higher than B from 10 a. m. to 5 p. m. and the difference is especially noticeable in the afternoon hours. The daily excess A over B is 78 gram-calories.

THE EFFECT OF SLOPE UPON THE QUANTITY OF SOLAR RADIATION RECEIVED PER UNIT OF SURFACE.

Prof. H. H. KIMBALL.

Let λ equal the latitude of the place, and C the angle of slope. For a south slope the angle of incidence of the solar rays with the surface for different hour angles of the sun will be the same as on a horizontal surface at latitude $\lambda - C$. The possible hours of sunshine with *south* or *minus* solar declination will not be changed; but for *north* or *plus* solar declination they will be the same as for latitude $\lambda - C$. For a north slope the angle of incidence of the solar rays with the surface for different hour angles of the sun will be the same as at latitude $\lambda + C$. The possible hours of sunshine with *north*, or *plus* solar declination will not be changed; but for *south*, or *minus* declination they will be the same as for latitude $\lambda + C$.

Thus, on a south slope of 7 per cent, or 4°, at latitude 35°, the angle of incidence of the solar rays will be the same as on a horizontal surface at 31° N., and on a south slope of 35°, or 70 per cent, at latitude 35°, the angle of incidence of the solar rays will be the same as on a horizontal surface at the equator, and from March 21 to September 21, inclusive, the hours of possible sunshine will likewise be the same, namely, 12 hours. On a north slope of 45°, or 100 per cent, at latitude 45° N., the angle of incidence of the solar rays will be the same as on a horizontal surface at the north pole. It will receive sunshine only between March 21 and September 21, and the possible hours of sunshine will be the same as at latitude 45°. Such a surface will therefore receive less solar radiation than a horizontal surface at the North Pole.

In the case of a slope facing α degrees in azimuth, the angle of incidence of the solar rays will be the same as on a horizontal surface at a point on a great circle passing through the slope at right angles to it and as many degrees removed as the angle of the slope. We may locate this point in latitude and longitude by the solution of the right-angled spherical triangle of which C, the angle of slope, is the hypotenuse; α is one of the angles, the side b is the difference in ~~longitude~~ latitude between the point and the slope, and side a is the difference in ~~latitude~~ longitude. The computation equations are $\tan b = \frac{\cos \alpha}{\cos c}$, and $\sin a = \sin \alpha \sin c$.

Example: At Wagon Wheel Gap, Colorado, at latitude 37° 46′ north, longitude 106° 53′ west, and elevation about 10,000 feet, are four slopes, A–2, B–2, A–1, and B–1, facing south 56° east, south 45° east, north 24° west, and north 24° east, and with angular slopes of 34° 20′, 30°, 31° 20′, and 37° 30′, respectively. The points where horizontal surfaces are parallel to these slopes are as follows:

A–2, latitude 16° 52′ north, longitude 79° west.
B–2, latitude 15° 34′ north, longitude 86° 11′ west.
A–1, latitude 66° 51′ north, longitude 119° 6′ west.
B–1, latitude 72° 48′ north, longitude 92° 33′ west.

The solar-radiation intensities upon these slopes has been computed upon the assumption that at normal incidence the intensity is as given in Table 5c, MONTHLY WEATHER REVIEW, Nov., 1919, **47**: 774 for latitude 37° 46′ increased by 1 per cent for the increased elevation at Wagon Wheel Gap. The results are given in Table 14.

On slopes A–2 and B–2, where the radiation intensity is high throughout the year, the snow that falls disappears quickly, as elsewhere shown. On slopes A–1 and B–1, which receive no direct solar radiation in midwinter and a greatly reduced amount throughout the year, the snow accumulates to a great depth..

TABLE 14.—*Radiation intensity upon slopes at Wagon Wheel Gap, Colorado.*

[Gram-calories per minute per square centimeter of surface. Apparent Time.]

Slope.	Date.	Gram-calories.							
		5 a. m.	6 a. m.	7 a. m.	8 a. m.	9 a. m.	10 a. m.	11 a. m.	12 m.
A–2.....	Dec. 21	....	....	....	0.53	0.92	1.08	1.09	0.98
	Mar. 21	....	0.07	0.73	1.11	1.34	1.45	1.44	1.31
	June 21	0.12	.51	.84	1.12	1.29	1.40	1.39	1.27
B–2.....	Dec. 21	....	....	....	.49	.89	1.06	1.13	1.07
	Mar. 21	....	.06	.63	1.02	1.29	1.44	1.48	1.40
	June 21	.08	.41	.74	1.03	1.25	1.38	1.41	1.34
A–1.....	Jan. 21	....	....	....	....	....	....	.02	.08
	Feb. 21	....	....	....	....	.06	.15	.26	.32
	Mar. 21	....	....	.03	.17	.32	.45	.55	.60
	June 21	.03	.28	.45	.65	.82	.96	1.06	1.11
B–1.....	Feb. 21	....	....	....	.04	.11	.15	.17	.16
	Mar. 21	....	.01	.17	.29	.38	.44	.46	.45
	June 21	.15	.43	.61	.74	.84	.90	.93	.93

TABLE 14.—*Radiation intensity upon slopes at Wagon Wheel Gap, Colorado*—Continued.

Slope.	Date.	Gram-calories.								Daily total.
		1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.	6 p.m.	7 p.m.	8 p.m.	
A-2......	Dec. 21	0.77	0.50	0.18	......	......	......	......	......	379
	Mar. 21	1.08	.77	.41	......	......	......	......	......	588
	June 21	1.28	1.07	.80	0.17	......	......	......	......	643
B-2......	Dec. 21	.89	.78	.32	.03	......	......	......	......	402
	Mar. 21	1.20	.92	.57	.21	......	......	......	......	596
	June 21	1.17	.93	.64	.32	0.01	......	......	......	641
A-1......	Jan. 21	.08	.01	......	......	......	......	......	......	11
	Feb. 21	.33	.29	.22	.11	.01	......	......	......	105
	Mar. 21	.61	.57	.49	.36	.20	0.01	......	......	259
	June 21	1.12	1.07	.98	.87	.63	.42	0.06	......	608
B-1......	Feb. 21	.12	.05	......	......	......	......	......	......	46
	Mar. 21	.40	.33	.23	.11	.09	......	......	......	181
	June 21	.88	.80	.71	.50	.45	.30	.11	......	554

SOIL TEMPERATURE.

The superficial soil layers receive and absorb incoming solar energy by day and lose heat as outgoing radiation by night. Whenever, therefore, the incoming radiation is in excess of the outgoing, the temperature of the soil rises and in due season reaches an annual maximum, thence receding to the annual minimum in midwinter. As in the case of air temperature, there are also short periods of temporary rises and falls in the temperature of the soil, as well as the more gradual seasonal progression. The magnitude of the accidental changes is largely a matter of the depth below the surface at which measurements are made. In this discussion we are concerned almost wholly with the seasonal changes at a depth of 12 inches, although observations of soil temperatures at a depth of 48 inches are also available. Between 5 and 6 years observations are available for both watersheds, and the D station representing the extreme upper portion of watershed A. The detailed weekly means for both slopes of the two watersheds are given in Table 15.

TABLE 15.—*Weekly mean soil temperature, 12 inches below surface.*

Date.	North slopes, 12 inches.		South slopes, 12 inches.		Date.	North slopes, 12 inches.		South slopes, 12 inches.	
	A.	B.	A.	B.		A.	B.	A.	B.
Jan. 7	19.9	24.0	29.8	26.6	July 1	41.6	46.1	54.7	56.3
14	19.1	23.5	28.6	25.9	8	43.3	47.1	54.8	56.3
21	19.2	23.3	28.4	25.6	16	45.1	48.0	53.7	55.6
28	18.7	23.1	27.7	25.0	23	47.2	48.7	54.2	55.7
Feb. 4	19.1	22.9	28.0	25.4	30	47.9	48.7	53.6	54.8
11	18.7	23.4	27.9	25.8	Aug. 6	48.1	49.3	53.7	55.0
18	18.7	23.5	28.3	26.6	13	47.6	49.3	53.3	54.5
25	19.4	23.7	28.7	27.1	20	47.4	48.3	52.0	53.2
Mar. 4	20.3	24.2	28.6	28.5	27	46.5	48.0	51.8	53.1
11	20.4	24.3	29.1	28.0	Sept. 3	45.5	47.4	51.1	52.4
18	21.1	24.8	31.5	28.9	10	44.4	46.2	50.8	51.5
25	21.3	25.1	31.2	30.7	17	42.3	44.2	48.8	49.8
Apr. 1	22.1	25.8	32.0	32.2	24	38.8	42.4	48.7	49.3
8	23.4	26.8	32.5	33.5	Oct. 1	36.4	40.6	46.7	46.6
15	24.8	28.1	33.4	34.6	8	35.4	39.7	45.8	45.1
22	26.9	29.4	33.8	35.1	15	34.0	37.6	44.1	42.4
29	29.7	30.2	35.4	37.0	22	32.8	35.8	42.5	41.4
May 6	31.6	31.2	36.4	37.5	29	32.3	34.5	41.7	40.0
13	31.8	32.7	38.8	39.7	Nov. 5	31.6	33.3	40.9	39.4
20	32.1	34.2	40.6	42.4	12	31.1	32.7	39.8	37.5
27	32.1	36.2	42.2	43.8	19	29.1	31.0	36.4	34.3
June 3	32.2	38.0	43.7	45.2	26	25.8	29.4	36.4	33.6
10	34.4	39.4	45.0	46.9	Dec. 3	23.2	28.0	35.3	31.9
17	37.2	41.9	49.9	51.8	10	22.6	26.9	33.9	30.1
24	39.5	44.1	52.6	53.8	17	21.3	26.6	32.0	27.7
					24	20.6	24.9	30.3	27.9
					31	20.0	24.2	29.9	26.7

The very decided topographic contrast between different portions of the same watershed is responsible for the differences in both air and soil temperatures, particularly the latter, which are found to exist between north and south slopes. It is impracticable to combine the soil observations into a mean that will truly represent the watershed as a whole; hence this discussion will be by corresponding slopes on the two watersheds. The south slopes form approximately about 30 per cent of the total area of the respective watersheds. Strictly speaking, the mean values of Table 14 refer only to the area in the immediate vicinity of the observing station. The air and soil temperature observations were made at the principal meteorological stations, A–1, A–2, and B–1, B–2, representing the lower portion of the watersheds.

North slopes.—B is warmer than A by 3.2° F. on the average of the year, the greatest difference, 4.8°, being in June. The soil temperatures then approach but do not reach equality, the difference for August being 1.4°, B being the warmer. A rather wide departure in October is followed by a second approach toward equality in the second week in November, doubtless due to the cooling of the first snow cover of the season. The soil temperatures of the two slopes then separate and remain about 4.0° apart on the average until the thawing season of the ensuing spring brings them practically together for a short time at 32° each in the middle of May. The wide separation in June may be due to local conditions of soil moisture at station A–1, since, as may be seen from the figures of Table 14, the weekly means for that station in the spring remain at substantially 32° from May 6 to June 3, whereas the means for the corresponding slope of B show a steady rise, so that by June 3 the mean of the north slope of B is 6.2° higher than A. In view of the great specific heat of water, it may be argued that saturated soil at 32° will have a tendency to change its temperature slowly. The soil-moisture observations for June show that the north slope of A has on the average a greater moisture content than the north slope of B. This wide divergence is not apparent in the records of the south slopes.

South slopes.—The south slope of A is warmer than the corresponding slope of B from October to March, inclusive, and slightly colder in the remaining or warm weather months. The excess of south slope A over south slope B for the cold months averages 2.3°; the average excess of B during the summer months is 1.1°.

Lag between air and soil temperatures.—As might be expected, the annual maximum soil temperature is reached on the south slopes and at the D station about a month earlier than on the north slope stations. At D there is no appreciable lag at a depth of 12 inches; at 48 inches the lag is about a month. The north slope of B appears to respond to insolation more readily than the corresponding slope of A, because it is consistently warmer and in some years the annual maximum temperature is reached concurrently with the annual maximum air temperature. This happened on the A watershed in but a single year, viz, 1917.

Influence of snow cover.—With the coming of a snow cover in autumn, even though light, the soil temperature to a depth of 12 inches sinks for several days and continues to fall slowly until it reaches the winter minimum during the first week in February on B and the second week on A.

The amount of temperature fall at a depth of 12 inches caused by a slight snow cover seems to depend upon the soil temperature at the time snow fell; thus, a relatively light snowfall when the soil temperature is 4 or 5 degrees above freezing will cause a steady fall tor five days at least, amounting on the average to about a degree a day. If, however, the soil temperature is near the freezing point when the snow comes, the fall in temperature will average but a fraction of a degree a day and may even rise slightly for a day or so. The cooling appears to be nearly equal on the two watersheds and is, if anything, a little greater on A than B, and the temperature sinks to a lower level on the north slope of A than on the corresponding slope of B.

The soil on the south slopes naturally responds to insolation more freely than that on the north slopes for reasons before given, also because of the fact that since the snow cover melts earlier, the bare soil begins to receive and absorb solar heat about a month sooner than on the north slopes.

The differences in soil temperature herein set forth must have a bearing upon the snow melting in the autumn and early winter.

PRECIPITATION.

The precipitation is measured daily at five points within walking distance of the headquarters station, viz, at station C (headquarters), which may be considered as representative of the southern portion of both watersheds, in watershed A and B respectively, at the two slope stations A-1 and A-2, B-1 and B-2. Recording rain-gages of the tipping-bucket type are in operation during the warm season at stations C and D and the records from these stations are used to apportion the hourly amounts in both watersheds throughout the 24 hours. The watershed precipitation, midnight to midnight, is determined by taking the larger of the two quantities recorded at the two rainfall stations in each watershed, adding to that quantity the amount of the precipitation at D and dividing the sum by 2.

The watershed precipitation as thus determined is given in the tables of Chapter III (see Table 36). On the average of eight years, watershed A has a mean annual precipitation of 21.02 inches and watershed B of 21.09 inches, or practically the same. The greatest difference in any one year was 1.03 inches in 1912-13, B having the greater amount.

In the revision of the program of meteorological observations effected in 1913, the precipitation year was made to begin November 1 instead of January 1. Later, for reasons which will appear in Chapter III, the year was made to begin October 1.

Colorado being remote from any large body of water and somewhat south of the average path of cyclones, does not at any season receive a generous amount of precipitation. The greatest average for the State, 20 to 25 inches, occurs on the western slope of the Rocky Mountains at altitudes above mean sea level of 10,000 feet and over. While the extreme upper part of both watersheds has an altitude somewhat above 10,000 feet, the situation of the area, with respect to the westerly winds, is not favorable to heavy precipitation, since westerly to northerly winds are descending winds and consequently dry. The precipitation is very nearly equally divided between rain and snow, with the former about 4 per cent greater than the latter; thus, rain 52 per cent and snow 48 per cent.

There is a well-marked rainy season in July and August, at least 55 per cent of the rain falling in those months. Precipitation as rain may occur as early as April and as late as October, although in late spring and early autumn, when beginning as rain, it is quite apt to change to snow before it ends. Snow in considerable amounts may fall in the latter part of September, but the real beginning of the snow season may be fixed as the last week in October. The first snowfall usually disappears by melting and evaporation, and it is not until the temperature during the afternoon hours does not rise above freezing that the snow cover may be said to be permanent for the winter.

Rainfalls of great intensity rarely occur at Wagon Wheel Gap. During the eight years considered but a single heavy 24-hour rain occurred, viz, on October 5-6, 1911.

Greatest amount of precipitation in 24 hours.—The greatest amount of precipitation that occurred as rain or snow for each month from the beginning of observations to June 30, 1919, is given in Table 16. The data are for the C (headquarters) station. The maximum amounts for the months May to October occurred as rain, for the remaining months as snow. This table clearly shows that heavy rains as much as 2 inches in 24 hours are the exception, but one such having occurred in the eight and one-half years of record.

TABLE 16.—*Greatest amount of precipitation in 24 hours (inches an hundredths).*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1910	......	......	......	......	......	......	......	......	......	......	0.40	0.20
1911	0.36	0.63	0.47	0.18	0.31	0.44	0.71	1.27	0.56	2.60	.36	.67
1912	.20	.23	.46	.42	.13	.53	.77	.63	.14	.69	.37	.35
1913	.32	.34	.43	.27	.21	.75	.61	.77	.98	.27	.45	.54
1914	.83	.40	.30	.22	.60	.67	1.22	.48	.72	.58	.01	.45
1915	.38	.68	.11	.60	.37	.29	1.00	.73	.88	.25	.92	.78
1916	.63	.12	.42	.37	.24	.11	1.11	.89	.37	1.03	.16	.24
1917	.75	.26	.24	.98	.43	.13	.69	.39	.25	.09	.55	.18
1918	.30	.47	.83	.47	.09	.20	.82	.89	1.04	.36	.85	.58
1919	.04	.29	.69	.38	.40	.56	......	......	......	......	......	......

Intensity of precipitation.—To present statistics of intensity of precipitation in some detail, the 24-hour precipitation (rain or snow) has been classed according to the scale shown in Table 17. Since, however, the runoff from snow appears at the end of the cold season and is not immediately effective in producing increased streamflow, the *rain only* has been classified in groups according to intensity of the 24-hour amounts. It is considered that rains of 0.10 inch and less in the summer as a rule serve merely to replenish losses due to transpiration and evaporation and do not directly effect streamflow. Rains greater than 0.10 inch may be considered effective in producing a slight increase in streamflow, depending, of course, so far as the lower limit of the scale is concerned, upon conditions of soil moisture and other factors. With a saturated soil a precipitation so small as 0.01 inch will produce a measurable response in streamflow.

The result of this second classification of rains gives the following very interesting results (in hundredths of an inch):

	Average intensity of rains.				
	June.	July.	August.	September.	October.
A........	0.26	0.33	0.30	0.32	0.40
B........	.31	.33	.30	.35	.46

This tabulation shows conclusively that the intensity of the rains is practically the same for each month of the season and substantially the same on both watersheds, with a tendency to be greater on B, at times, than on A.

TABLE 17.—*Intensity of rainfall A (days with total precipitation).*

	Days with—						Total effective rains (days).	Total rainy days, 0.02 inch or more.
	T. to 0.01 inch.	0.02 to 0.10 inch.	0.11 to 0.30 inch.	0.31 to 0.50 inch.	0.51 to 1 inch.	1 inch and over.		
1912.......	42	59	43	13	3	0	59	118
1913.......	67	61	36	10	11	0	57	118
1914.......	58	67	36	11	9	0	56	123
1915.......	50	45	32	13	8	2	55	100
1916.......	37	63	32	17	9	1	59	122
1917.......	66	58	26	14	5	1	46	104
1918.......	77	62	43	12	8	2	65	127

The rainfall intensity has been independently computed by dividing the average monthly precipitation by the average number of rainy days, classing as a rainy day all days with 0.02 inch of precipitation or more.

The results are shown graphically in figure 16, and are explained as follows: The average monthly precipitation (adjusted for inequality in length) is shown by the rectangular figures opposite the respective months. The heavy line in the center of the rectangle represents the average number of rainy days and the shaded portion of the rectangle at the bottom gives the intensity of the precipitation as above indicated. The intensity by this method is somewhat less than when only the so-called effective rains are considered.

Thunderstorms.—Much of the summer rain comes in the form of afternoon thundershowers in July and August. Thundershowers may occur, however, as early as April, before the snow cover has disappeared from north slopes. The amount of rain which falls in these early thundershowers rarely exceeds half an inch, the greater part of which is absorbed by the snow cover. Since the weather associated with April and May thunderstorms generally turns cooler and the precipitation which begins as rain turns to snow, the run-off never assumes flood proportions. The thunderstorm season is from the last half of April to the middle of October, and the months of greatest frequency July and August. The average number per season is 70.

Snowfall.—While the snowfall forms a little less than 50 per cent of the total precipitation, it yields considerably more than 50 per cent of the run-off. The total precipitation in the months November to March, inclusive, is in the form of snow, and the precipitation of

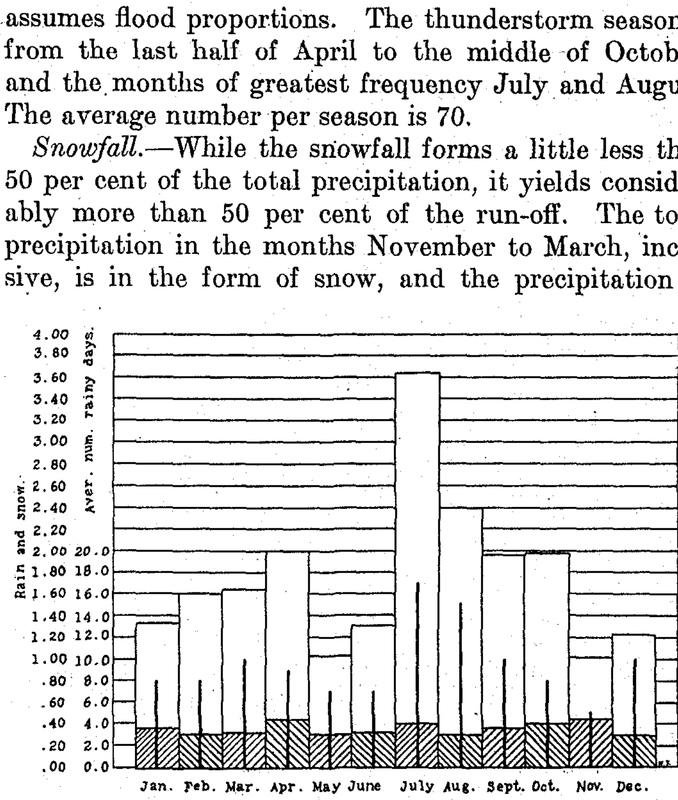

FIG. 16. Intensity of precipitation.

April is also 91 per cent snow. While a trace of snow may even fall in the summer months, the real transition months are June with 6 per cent of snow and October with 38 per cent. The snowfall of September is apt to be light, wholly disappearing before the cold-season snowfall sets in. The average depth of snow per season is 113.3 inches, with an equivalent water content of 9.94 inches. The range in depth from year to year is from 149.7 inches in 1916–17 to 80.7 inches in the following year. March, on the average of 9 years, is the month of maximum snowfall, 18.5 inches, with January, 17.9 inches, a close second; when, however, the months are corrected for unequal length, February ranks second with 17.98 inches and January third with 17.54 inches.

Snowfall measurements.—The depth of snowfall and water equivalent, determined by weighing, is observed daily about 9 a. m., at stations C, A–1, A–2, B–1, and B–2. It is determined at six-day intervals at the D station, and the amount for each day is apportioned from the measurements made on the two watersheds. Finally, beginning on March 1, to anticipate the melting season by a few weeks, the depth and density of the snow over the two watersheds is observed at the snow scales or snow stakes which were installed at various places on both watersheds. There are 18 snow scales on A and 14 on B. Table 18 is a statement of the details of the location of each scale to which has been added, for convenience in the discussion, the average date of disappearance of snow at each scale. The arrangement of the table is by slope rather than consecutively by the serial number of the snow scale.

TABLE 18.

Watershed A. Average date of disappearance of snow and details of snow scales.

No. of scale.	Direction of slope.	Angle of slope.	Average date of melting.
	°	° ′	
4	N. 2 E	42 00	May 15
7	N. 2 E	25 20	May 10
1	N. 12 E	34 10	May 16
10	N. 30 E	13 50	May 17
17	N. 40 E	21 30	May 11
14	N. 46 E	15 50	May 22
15	N. 52 E	2 00	May 14
11	N. 72 E	16 50	May 13
8	N. 82 E	9 30	May 11
6	N. 82 E	33 50	Apr. 26
9	N. 90 E	11 20	May 7
13	S. 84 E	10 50	May 13
5	S. 40 E	25 50	Mar. 26
18	S. 36 E	24 50	Mar. 7
12	S. 32 E	23 40	Mar. 16
2	S. 70 E	34 20	Apr. 1
3	Level	....	May 2
D	N. 50 E	24 40	May 23

Watershed B. Average date of disappearance of snow and details of snow scales.

No. of scale.	Direction of slope.	Angle of slope.	Average date of melting.
	°	° ′	
1	N. 12 W	15 30	May 16
10	N. 12 W	26 50	May 26
5	N. 6 W	26 40	May 11
4	N. 22 E	21 50	May 9
16	N. 26 E	16 20	May 20
15	N. 29 E	11 50	May 23
14	N. 52 E	2 00	May 19
11	N. 66 E	22 10	May 12
13	N. 70 E	9 10	May 12
9	S. 84 E	10 50	May 16
8	S. 74 E	32 40	Apr. 23
2	S. 66 E	25 30	Mar. 20
12	S. 52 E	21 40	Apr. 6
6	S. 50 E	26 50	Mar. 10
7	Level	....	Apr. 24
D	N. 50 E	24 40	May 23

In selecting the points for snow measurement reference was had in some measure to the main types of forest cover found on the area and endeavor was made so to place the scales as to obtain the best possible representation of the distribution of snow. In general, snow-scale areas represented by scales Nos. 8 to 17 and D, both inclusive, on watershed A, are wholly above the 10,000-foot contour line. Areas Nos. 3, 6, and 12 are, in part, above that contour. On the B watershed, areas Nos. 4, 9, 10, 11, 12, 13, 14, and 15 are wholly above the 10,000-foot contour and areas Nos. 8 and 16 are in part above that contour. The location of snow scales or stakes may be seen by reference to figure 17.

The disappearance of snow.—The four typical south-slope snow scale areas on A, Nos. 2, 5, 12, and 18, have an average direction of slope south 44° east and the average angle of slope with the horizontal is 27° 10′. The four typical south-slope areas on B Nos. 2, 6, 8, and 12, have an average direction of slope of south 60° east and an average angle of slope of 26° 40′, this being almost identical with the south slopes on A, except that B has a little more easterly aspect than A. The average date of disappearance of snow at the four typical south-slope areas on both watersheds is for A March 20 and for B March 30. For the four typical north-slope areas, with nearly the same direction and angle of slope, the average dates are as follows: A May 19, B May 16. Whence it appears that the snow disappears, on the average, about 10 days earlier on the south slopes of A than on the corresponding slopes of B and about 3 days later on the north slopes than on the corresponding slopes of B.

The areas used in computing the above averages were north slopes A Nos. 1, 4, 14, and 15, north slopes B Nos. 1, 4, 14, and 16.

Snow disappears earliest from area No. 18 on A and No. 6 on B. Both are steep southeast slopes, No. 18 being practically all above 10,000 feet elevation, while No. 6 is about 300 feet lower. Snow disappears last, of course, from the higher east-northeast slopes of both watersheds. The average interval between the time of disappearance on the respective slopes of A is 77 days, on B about the same, although in individual years snow-scale areas Nos. B 10, 15, and 16 retain some snow after the cover has entirely disappeared from A. The melting season is, therefore, on the average, about 75 days in length.

On the lower part of the area the mean temperature for March is 24.2°, but for the hours 1, 2, 3, 4, and 5 p. m., the mean is 32° or over. At the D station, however, representing the higher portions of the area, the mean maximum for March is but 31.7° and it is not until April that the mean temperature of the afternoon hours in the upper portion of the watershed passes above freezing, hence the difference in elevation between the upper and lower portions of the area corresponds to about a month's lag in temperature.

RELATIVE HUMIDITY.

The relative humidity may be defined as the ratio of the amount of vapor actually present to that which might be present if the air was saturated at the existing temperature. It is commonly expressed as a percentage. Humidity may also be expressed in the expansive force the vapor exerts, or in its weight in grains per cubic foot of air. In this case the amount of vapor actually present at any time is called the absolute humidity.

The relative humidity is determined daily from observations of the sling psychrometer about 9 a. m. at the two north-slope stations, and these stations are equipped with hygrographs of the Richards type. The numerical values from the hygrographs in terms of vapor pressure were tabulated for about a year, but on account of the very considerable labor involved in the tabulation and the problematical value of the results, the tabulation of the hourly values was discontinued early in the experiment. The fragmentary hourly values show that the pressure of water vapor in winter is at a maximum during the warmer hours of the day. As the warm season approaches, however, the maximum occurs in the forenoon hours, 9 or 10 o'clock, and continues to occur about these hours, until November, when it reverts to the afternoon hours.

The relative humidity is greatest in the cold part of the year and least in the warm part, the mean values (monthly means considered), are for B 78 per cent in December and 47 per cent in May; for A 71.5 per cent in August and 43.8 per cent in May.

The two watersheds compared.—Table 19 contains the monthly means of relative humidity derived from a single observation made daily at 9 a. m. at the north slope stations of the two watersheds. The monthly mean vapor pressure for the same hour has been added.

TABLE 19.—*Monthly mean relative humidity and vapor pressure.*

[Humidity in percentages. Vapor pressure in thousandths of an inch of mercury.]

	January.	February.	March.	April.	May.	June.
R. H. A-1	67.3	67.0	61.3	55.8	43.8	48.5
R. H. B-1	77.0	74.6	67.6	61.1	47.4	47.5
V. P. A-1	.052	.054	.071	.100	.116	.185
V. P. B-1	.056	.058	.078	.115	.136	.196

	July.	August.	September.	October.	November.	December.	Annual.
R. H. A-1	68.1	71.5	67.6	63.0	64.1	70.1	62.3
R. H. B-1	66.8	70.6	70.1	68.8	71.8	78.0	66.8
V. P. A-1	.279	.260	.192	.118	.070	.049	.129
V. P. B-1	.291	.275	.205	.130	.077	.053	.139

It is clear from the above figures that the relative humidity of watershed B is considerably greater in the months October to May and slightly less in the months June to August than that of A for the corresponding months. The changes in relative humidity from one month to the next are worthy of notice. In general, the relative humidity diminishes to a minimum in May on both watersheds, the diminution from April to May amounting on the average to from 12 to 14 per cent. From the minimum of May to the beginning of the rainy season in July there is a decided increase which comes almost wholly in the period June to July. This increase amounts to nearly 20 per cent on the average, although in a single year, 1916, it amounted to 39.5 per cent.

The vapor pressures are computed, of course, having regard for the existing temperatures, and are therefore a better index of the moisture content of the atmosphere than the relative humidity. The figures in the lower half of Table 20 show that the moisture content of the air at the B–1 station is slightly greater than for the corresponding slope of A throughout the year. This constant difference in the means is rather puzzling. The wind movement at the B–1 station is very weak, as will be shown elsewhere, less than 1 mile per hour. To determine whether the difference in the means is due to large and infrequent differences in the monthly means or to small and constant differences, Table 20 has been formed.

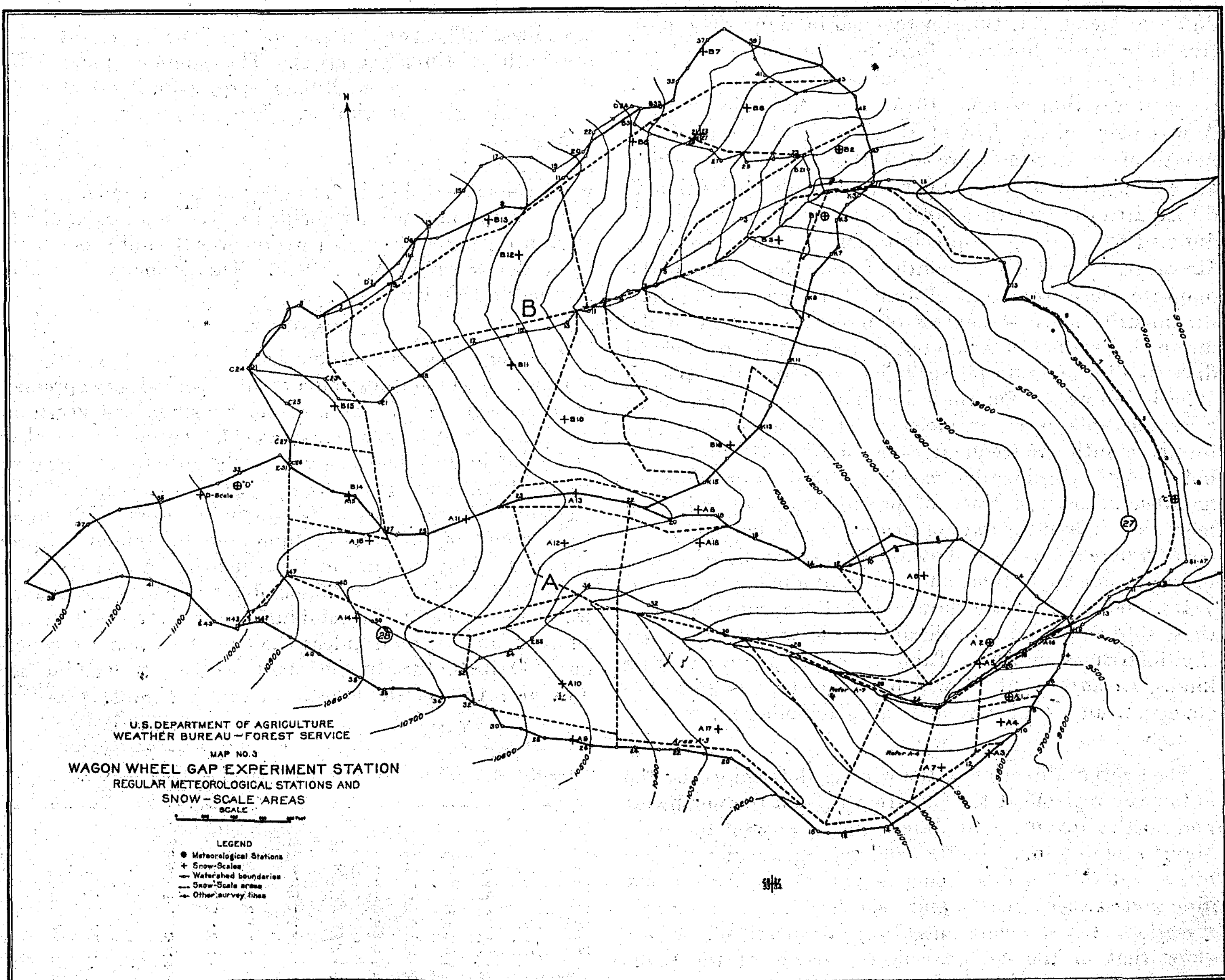

FIG. 17. Meteorological stations, snow scales, etc.

TABLE 20.—*Differences in vapor pressure (A minus B).*

Year.	November.	December.	January.	February.	March.	April.
1910–11	....	....	+0.002	+0.001	−0.004	−0.009
1911–12	−0.007	−0.002	.000	− .002	+ .005	− .007
1912–13	− .002	− .002	− .005	− .004	− .009	− .018
1913–14	− .009	− .002	− .011	− .007	− .012	− .020
1914–15	− .012	− .005	− .007	− .009	− .008	− .018
1915–16	− .007	− .006	− .009	− .005	− .014	− .020
1916–17	− .009	− .008	− .005	− .007	− .008	− .009
1917–18	− .006	− .012	− .002	+ .001	− .005	− .025
1918–19	− .004	+ .001	....	....	....	....
Mean	− .007	− .004	− .005	− .004	− .007	− .016

Year.	May.	June.	July.	August.	September.	October.
1910–11	−0.017	−0.005	+0.003	+0.001	−0.009	−0.017
1911–12	− .018	− .018	− .012	− .018	− .018	− .017
1912–13	− .021	− .033	− .029	− .030	− .016	− .012
1913–14	− .019	− .024	− .020	− .015	− .013	− .015
1914–15	− .014	− .013	− .018	− .024	− .017	− .014
1915–16	− .016	+ .028	− .018	− .019	− .012	− .015
1916–17	− .017	+ .011	+ .009	− .004	− .012	+ .003
1917–18	− .035	− .034	− .012	− .008	− .006	− .005
Mean	− .020	− .011	− .014	− .014	− .013	− .012

In general, the differences A minus B are uniformly negative and small, although there are some rather large differences and sometimes a reversal of sign. The positive differences, however, form but 10 per cent of the total cases considered. The most pronounced case of reversal was that of June, 1916, when the atmosphere at A was more moist than at B. June, 1917, was also a month of greater moisture at A than at B. In seeking an explanation of this apparent anomaly, attention is directed to the fact that both of these months were dry, June, 1916, having a precipitation of but 0.10 inch. However, May, 1918, a month of wide departure in the opposite sense from that of June, 1916, was also a very dry month, hence the excess of moisture content of the air on B over that of A can not be referred to any general dryness of the atmosphere which envelops the Wagon Wheel Gap area. On the other hand, the months with a considerable excess in moisture at B were almost uniformly months of frequent rains; June, 1913 and 1918, both show a considerable excess and both were showery months, at least a trace of precipitation occurring on more than half of the days of the respective months.

Elsewhere it has been shown that there is slightly more precipitation on B than on A in individual months and years, and that as the duration of the record increases these differences tend to diminish. It would seem that the differences shown in Table 21 are of more enduring kind. In any event, it will be interesting to note the change, if any, that may arise after denudation.

WIND.

The average direction of the wind as determined by the automatic register at the C station is from the northwest and north, November to March, and from west to south, May to September. In the cold season the direction is quite variable, winds being experienced from every direction except east and southeast. The hourly directions for a single year were transcribed. These show that in the cold season the winds of the night hours are quite uniformly from the northwest toward the bottom of the river valley, backing during the warmer hours of the day (10 a. m. to 4 p. m.) to the north and shifting back to the northwest at 5 p. m.

In the warmer months the winds from midnight to 6 a. m. are from the west, backing to the north and northeast, that is, down the valley from 8 a. m. to noon. From 1 to 6 p. m. they are south or up the valley, shifting to the southwest at 7 p. m. and to the northwest at 10 p. m. This is graphically indicated in figure 18. In the warm months a true mountain-valley wind prevails.

The velocity of the wind is uniformly light. At the D station, with a comparatively free exposure, the average

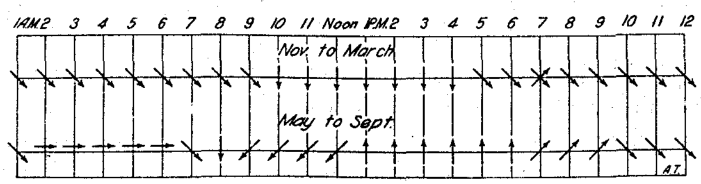

FIG. 18. Average hourly wind direction.

hourly velocity for the year is but 6.2 miles per hour.

At the C station, with a free exposure to all except north and west winds, the annual average velocity is but 2.6 miles. The two north-slope stations, A–1 and B–1, are both in timbered areas. The anemometer in the first is exposed in a small open spot, a former rock-slide in the Douglas fir timber. The B–1 anemometer is exposed in a small cleared space in the aspen and young fir, well protected from the wind. The average hourly wind velocity at A–1 is 2.2 miles; at B–1, 1 mile.

The maximum wind velocity for five minutes at the C station during a 29-month period was 32 miles per hour from the south in May, 1913. This velocity was also reached in October, 1912.

SUNSHINE.

The sunshine is automatically recorded at the C station. The monthly and annual mean values expressed as a percentage of the possible sunshine are given in Table 21. Sunshine is greatest in October and November and least in July and August, although June in the two years 1916 and 1917 had a high percentage. The character of the season is somewhat dependent upon the amount of sunshine in June and the amount of precipitation which occurs in that month. An early flood, as in 1913, with full sunshine in June, depletes the storage water in the watersheds and makes for low run-off in late summer and autumn unless the summer rains are generous. Quite naturally the months of least sunshine are July and August, the months of summer rains.

TABLE 21.—*Sunshine, per cent of possible.*[1]

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec	Annual.
1910	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	70	63	.....
1911	46	44	49	50	60	51	31	47	43	60	58	50	49
1912	61	54	39	38	52	43	40	52	61	51	64	62	51
1913	55	57	56	61	52	39	49	40	42	53	45	52	50
1914	55	66	70	42	44	52	29	42	55	53	70	55	53
1915	61	60	65	44	53	67	54	53	51	68	59	51	57
1916	48	67	65	55	67	74	43	42	63	60	71	57	59
1917	66	58	61	51	55	74	53	48	50	76	60	66	60
1918	52	58	54	59	66	57	45	49	52	56	58	50	55
1919	70	60	59	58	52	55	.....	.....	.....	.....	.....	.....	.....
Means	57	58	58	51	56	57	43	47	52	60	62	56	55

[1] Based on a sea-level horizon.

CHAPTER III.

PRECIPITATION AND STREAMFLOW.

The purpose of this chapter is to present the streamflow data obtained up to June 30, 1919, as the basis for a more or less empiric comparison of the behavior of stream B before and after the removal of the forest cover. It is not expected, however, merely to compare the eight-year period before denudation with a similar period following, either by use of means or the direct comparison of similar years in the two periods. Such a method would have very serious objections, especially if the two periods fell in different phases of one or more consecutive climatic cycles. Moreover, experience has shown that two years, or two melting periods, producing stream régimes which are in any degree similar must occur only at rare intervals. These facts make it necessary to go into an analysis of the streamflow, and the *causes* thereof, almost day by day. But, fortunately (and this is the respect in which the present experiment has an advantage over all others so far), it is not necessary to depend entirely, or even very largely, on the correct analysis of the factors *causing* Stream B to exhibit a given behavior. In both phases of the experiment the undisturbed behavior of stream A can be referred to, this behavior representing the best possible integration of all the factors which affect streamflow. The difficulty, and the real reason for so much analysis of causes has been undertaken, arises from the fact that both the time and degree of response of the two streams to any factor influencing the régime are somewhat dissimilar.

First, then, the various factors affecting streamflow will be discussed in a more or less abstract way but with particular reference to the special conditions. Following this, the statistical data available up to June 30, 1919, will be summed, in the light of that which has preceded, and certain "Rules" will be formulated which are to serve as the basis of calculations in the future, These calculation, in order to have statistical value, must:

1. Permit the drawing of a suppositional discharge curve for stream B, after denudation, which will show, with a very small probable error, how that stream might be expected to flow had the forest cover on B watershed not been disturbed.
2. Permit the comparison of the above curve with the actual discharge curve for any period, in such manner that the influence of the forest may be directly expressed in terms of higher or lower streamflow.

To meet practical requirements, it should be possible to calculate the suppositional discharge of B, and compare it with the actual, by reference to the behavior of stream A, and other guides, for:

1. The year as a whole.
2. The spring melting or flood period, when there is an abundance of water in all streams, and when, therefore, there is less concern with current discharges than with possible conservation for later discharge.
3. The summer period, when the water has the highest intrinsic value for irrigation, when time of delivery is a most important element, and when, therefore, the streamflow must be considered by very short periods.
4. The freezing period, or period from October 1 to the beginning of the next spring flood, when conservation is the main thing to be studied.

THE STREAMFLOW YEAR.

It is clearly obvious that the beginning of the precipitation and run-off years can not be arbitrarily chosen, but that they should conform as nearly as possible to the natural cycle of precipitation and runoff within the calendar year. It also seems obvious that effort should be made so to choose the period that whatever precipitation occurs in it will be measured as stream discharge, as largely as possible, during the same period. There will always be, whatever the period selected, a certain volume of ground water in the watersheds at the beginning and end of the period; it was therefore the object of the study to select a time when the volume of ground water in the two watersheds was approximately the same. Therefore October 1 was chosen as the beginning of the precipitation and run-off year instead of January 1, as in the usual climatological studies. Following are some of the considerations which led to the selection of this date. September 30 is for the majority of years the end of the season of greatest draft upon ground storage due to evaporation and transpiration. The streams are discharging at that time practically the same amounts. Table 22 gives the daily discharge on October 1 of each year in ten-thousandths of an inch over watershed.

TABLE 22.—*Daily discharges, Oct. 1.*

	A	B		A	B
1911....	0.0147	0.0124	1916....	0.0103	0.0101
1912....	.0109	.0117	1917....	.0107	.0103
1913....	.0105	.0106	1918....	.0076	.0079
1914....	.0099	.0096			
1915....	.0090	.0090	Mean...	.0104	.0102

Eliminating the large discharge of 1911, we have 0.0098 and 0.0099, for means.

Further argument, if necessary, against the use of November 1 as a starting point, as has been the practice in the routine calculations, is found in the fact that all precipitation in the form of snow which does not melt before October 31 will appear as run-off in the year subsequent to that to which it is accredited as precipitation. The amount of snow on ground at north-slope A–1 station on October 31 for each year, 1911 to 1918, both inclusive, is shown in Table 23.

TABLE 23.

Date (Oct. 31).	Snow on ground.	Date (Oct. 31).	Snow on ground.	Date (Oct. 31).	Snow on ground.
	Inches.		*Inches.*		*Inches.*
1911..........	8.9	1914..........	2.4	1917..........	T.
1912..........	7.0	1915..........	0.0	1918..........	T.
1913..........	T.	1916..........	3.6		

This table shows that in four out of the eight years there was an appreciable amount of snow on the ground at the end of October, the run-off from which would appear in the discharge year beginning November 1, although the precipitation would be accredited to the previous year.

Finally, owing to the fact that the discharge record previous to July, 1911, is more or less uncertain on account of leaks in the dams and the form of weir then in use, it has been thought best to start the discharge record with August, 1911. The greatest rain flood experienced thus far in the experiment occurred in the early part of October, 1911. If the discharge year be started on November 1, this great rain flood would be eliminated from the record, obviously an undesirable proceeding.

ANALYSIS OF STREAMFLOW.

The general behavior of the streams.—The most casual observation of any of the streamflow records obtained during periods of rain or melting snow shows the following points: (1) that stream A rises more rapidly than stream B: (2) that the maximum flow of A is reached sooner than that of B, and, therefore, during the early decline of A, stream B may be considerably higher; and (3) that before the flood has fully spent itself A may again attain the higher level, with a secondary and more steady volume of water.

These differences are all explainable by topography.

(1) Stream A receives a larger contribution of the first water falling directly into the stream in the case of rain, or melting along the stream banks in the case of snow, because it has a greater length of stream channel. With either rain or melting snow this advantage may be continued for many days, because the slopes through which the water must drain to reach the stream are both shorter and steeper than those on B. In other words, while B has 200 acres within an average distance of 950 feet of the stream, watershed A has an equal area within 670 feet. Since the flow down these slopes is relatively much slower than the flow in an open channel, it is evident that this width of slope has much more influence on the early flow than the length of the stream.

(2) After stream A has delivered its maximum flow, the longer slopes on B get into action, and not only are they later in delivering, but they may produce a higher flood because the extreme head of the watershed, being relatively near the dam, and hardly more distant from an open channel than the side slopes, delivers almost simultaneously with them. Thus B watershed, having more the shape of a bowl, within a few days of the flood crest may deliver a larger proportion of its total flood waters than A. Whether or not the crest flow on B is as great as on A will depend upon a number of factors, whether, for example, hourly, daily, or decade crests are referred to. A very rapid rise has the effect of amassing a large amount of water in stream A before B is well started, and of creating a higher short-period crest on A. On the other hand, the same rise will permit B to deliver a very large amount in the succeeding 10-day period and may cause a higher decade crest on B. Very different effects may, of course, be produced if the rapid melting of snow occurs after a period of slow melting which has disposed of much of the snow near stream A, since that *near* stream B does not melt so early.

(3) The higher flow of A late in the flood period (which may not be actually much higher when area is considered) is plainly due to the greater length of the watershed, or, in other words, to the slower draining out of the flatter ground more distant from the dam. This upper area, except during the heaviest melting period or in excessive rain, has no surface drainage, and hence its water is long in reaching the stream. The upper section of watershed A may practically be thought of as a separate area, such as does not exist with respect to Stream B. It has a stabilizing effect on stream A.

On the other hand, although this is a separate consideration, this high area on watershed A probably contributes little or nothing to the stream in the winter period, when B is actually higher, and considerably higher per unit of area, than A. This high, relatively flat ground has the appearance of becoming very dry in the fall; when once covered with a blanket of snow, since it has no southerly exposures, there is practically no melting for months, and, therefore, although the ground is not frozen to any great depth, there is no water contributed from it.

The streams involved in this experiment are perennial, and after observing that there is melting of snow on south slopes throughout the winter, it is not difficult to calculate that the flow for any ten days, or in fact for any day or hour, is made up (1) of any current precipitation or melting which may reach the streams directly, and (2) of a slower movement of water from the soil. This movement from the soil will vary with each addition to the soil moisture. Its total contribution to the stream for any period will depend not only upon the average amount of moisture in the soil, but upon the distance of that moisture from the stream. Thus the relative amount of moisture at any two points not similarly situated with respect to the stream not only will vary with additions of precipitation, but will depend upon the time since the last addition of moisture.

Each of these variable factors is different for the two watersheds. Any attempt to figure the source of the water, even when we know its volume in the streams, therefore, becomes simply appalling when one considers all of the factors involved; and when it is remembered that the most important of these factors, the accurate measurement of the rainfall or the water contributed from melting snow, is difficult of accomplishment the preparation of a formula which will express streamflow looms up as an impossibility.

For example, it must be conceded that the flow of either stream at any time is dependent upon the amount of water stored in the watersheds, or the "residual water," and upon the direct rainfall into the streams or water reaching the streams almost directly from surface flow or nearby seepage. Any water which does not reach the streams directly may be considered to augment the residual water.

Let A be the flow of A for any decade, and B the flow of B for any decade. Then,

$$A = P + x\ R$$

in which P represents a certain percentage of current precipitation, dependent on the amount of precipitation in the decade and its time position in the decade; R represents the residual water on the watershed, and x a percentage of that water which is more of less proportionate to the value of R, since R represents hydrostatic pressure.

Similarly:

$$B = P_b + yRb.$$

The use of R implies that the residual water on all parts of the watershed is *uniform, or at least that all* parts of the watershed are contributing to streamflow in proportion to their residual water. This assumption, as we have seen from the preceding general survey is probably incorrect, or at least far from precise.

The value of R may be roughly determined at any time when the flow is not influenced by rainfall by computing the effect of one or more day's flow upon the discharge. In other words, if a day's discharge of 100,000 cubic feet reduces the rate of flow by 5 per cent, we may assume that the amount of water to be discharged is approximately $20 \times 100{,}000$ cubic feet or 2,000,000 cubic feet, which figure may be reduced to terms of depth over watershed.

An attempt to calculate the residual water for watershed A, for a specific time, will show the factors involved and the impossibility of carrying any such calculation through a period of protracted melting. It also indicates the impossibility of a similar computation for watershed B when standard conditions of flow have been departed from.

At midnight August 3, 1911, the flow of A was 0.123 C. F. S. and at midnight August 7, 0.104 C. F. S., no precipitation having occurred This decrease of 0.019 C. F. S., or 15.45 per cent of the original discharge rate, is represented by a total discharge of 39,236.4 cubic feet of water, which, within these limits, might be construed to represent 15.45 per cent of the residual water on August 3. On this basis the residual water would have been 254,100 cubic feet.

It is obvious, however, that the decrease in rate of flow was brought about not alone by water discharged but also by water evaporated from the watershed. Taking years as a whole, the discharge could not be more than 30 per cent of the whole loss, and for early August was probably much less than this. To obtain an idea of the probable evaporation in August, the record may be consulted for the following period. From August 8 to 28, 1911, inclusive, there were frequent and effective rains, amounting in all to 2.99 inches over the watershed. At the termination of August 28 the rate of discharge of stream A was still 0.103 C. F. S., and there had been discharged in this period 210,027 cubic feet, or the equivalent of 0.2604 inch O. W. (on watersheds). In other words, 8.7 per cent of the precipitation had appeared as discharge, the residual water was presumably of the same amount as at the outset, and therefore it may be assumed that 91.3 per cent of the precipitation had been lost as transpiration and evaporation.

It is true evaporation occurs most freely while the precipitation is occurring and the surface of the ground, foliage, etc., is moist; but it is also true that in such cloudy weather the capacity of the air for moisture is much less than in clear weather. It may therefore be concluded that in clear August weather the stream discharge represents no more than 10 per cent of the water lost from the watershed.

Therefore the flow of stream A from August 4 to August 7, inclusive, probably represents only 1.54 per cent of the residual water on August 3 (midnight), and the amount of the latter may be calculated to have been 2,550,000 cubic feet, or 3.16 inches over the watershed. It becomes perfectly apparent from the above that while in August a flow of 0.123 C. F. S. might indicate approximately 3.16 inches O. W., at another time when evaporation was at a minimum such a flow might indicate only one-fifth as much residual water. The rate of discharge can not, then, be used directly as an index to the moisture conditions of the watersheds just preceding the flood rises. It is also plain that, since watersheds A and B have different drainage rates, their residual waters can never be assumed to correspond, and that no computation of residual water for watershed B under forest conditions would apply after denudation.

It thus becomes apparent that an analysis of the stream-flow data must be, instead of an examination and formulation of causes, a recitation of experiences so far obtained. In other words, it is reduced to an empiric basis. It can only be said that for specific times and seasons such and such relations between A and B discharges have existed in the past and therefore that for any other year, if the controlling conditions were not changed, similar relations, within the limits of probability, would exist. It is an obvious mathematical fact that *average* relationships would be more firmly established for definite times and seasons by further observations before denuding. In other words, the probable errors in the averages set forth would be decreased. The first phase of the study is not, however, concerned so much with *averages* as with individual years and with the probable or average variation of single years from the so-called normal, and it is doubtful if these average variations would be materially affected by adding new records.

Balance between precipitation and run-off.—Any consideration of the important relation between precipitation and run-off should be preceded by a clear statement of what is conceived to be the facts concerning the disposition of the precipitation which occurs either in the form of rain or snow. At Wagon Wheel Gap, as may be seen from the discussion of the climate, the division between rain and snow, on the average, is practically an even one, viz, 50:50, although in individual years the rainfall may exceed the snowfall by as much as 10 per cent, or vicé versa. The run-off from rainfall is different from that of snow in the fact that there is practically no immediate run-off from the latter as in the case of the former, and the amount of water which percolates into the soil is very much greater from snowfall than rainfall.

In the analysis of the stream discharge it is necessary of course to consider how precipitation, which occurs in the form of rain, is or may be disposed of.

It may be assumed that the water is divided in different portions, about as follows:

R_1. *Portion intercepted by trees, bushes, and other vegetation and objects of surface cover.*—This can properly include only such amounts as are permanently intercepted and never reach the soil or stream, but are either presently evaporated in place on the vegetation or possibly absorbed by it. The amount of this can not be much, except in case of numerous light showers, since it seems necessary to recognize that although foliage and vegetation may temporarily intercept a considerable amount of rain for a time, nevertheless after becoming thoroughly wet it may subsequently shed a considerable part of that temporarily intercepted. In some cases wind will set up motions in the boughs and foliage which will also cause subsequent release of water temporarily intercepted. A critical study of this phenomenon of interception is needed before definite conclusions and especially quantitative results can be formulated.

R_2. *Surface water and flow.*—This portion of the rainfall is more particularly in evidence during and for a short time after rainfall which is sufficient to induce this apportionment. During and after substantial rainfall innumerable rivulets of flowing surface water abound everywhere in a watershed, all tending toward some portion of the stream. In heavy rains much water actually reaches the stream derived wholly from this source, including of course water falling immediately into the stream itself. Surface flow at a distance from the stream may never reach the stream as strictly surface flow, but in its onward course will penetrate the soil and will then be more appropriately put into another category to be considered next.

The portion R_2 *surface water and flow* must, therefore, be limited to only that portion which actually reaches the stream by strictly surface flow and which in substantial and heavy rains produces typical flood conditions of flow and stages, even though of diminutive amounts. Floods due to surface flow generally rise suddenly and quickly subside without much tendency to prolonged or sustained flow. A few days of rainless weather, even without wind and sunshine, suffice to exhaust the water represented by R_2 and eliminate phenomena of surface flow from the streamflow.

R_3. *The portion of the rainfall which serves to replenish what is generally known as "underground waters" from which is derived the perennial supply of springs and streams.*—Since we find the streams flow perennially, to all intents and purposes, we must conclude that there is a relatively abundant reserve supply of water in the watershed even after protracted dry spells. So that R_3 must be regarded as becoming incorporated with the soil cover and augmenting the general reserve or permanent but variable water-content of the watershed. The daily and perennial flow of the stream draws constantly upon this water-content for its daily discharge, which steadily depletes the supply. Direct evaporation from the soil, and especially water losses by transpiration also draw upon the reserve water-content.

Rainfall, therefore, constantly replenishes the water-content of the watershed and is disposed of in three portions: R_1, intercepted by foliage and never influencing stream flow; R_2, surface flow, causing more or less sudden and transitory flood features of streamflow, and finally R_3, ground water, constituting and augmenting the water content of the watershed, upon which content the main features of the stream flow depend. This water-content is also drawn upon for phenomena of transpiration and evaporation.

The hourly, daily, or seasonal features of stream discharge are, of course, intimately related to the precipitation on the one hand and on the other on the way in which the water is apportioned in the R_2 and R_3 catagories, including the total water-content of the watershed at any time and the extent to which evaporation and transpiration are draining off or drinking up the reserve water before it can reach the stream.

Still confining attention to rainfall and summer conditions only, certain inferences follow more or less obviously from the considerations mentioned in the foregoing.

(1) Light gentle rains may be wholly expended in satisfying the demands of the R_1 apportionment, especially over all that part of the acreage of the watersheds which is thickly forested. Some contributions to the portions R_2 and R_3, especially the latter, may result from light rains over unforested acreage, but the influence is scarcely observable in the stream discharge. It is very important to recognize and bear in mind that only 0.10 inch of rain added to the soil once in each ten days, if wholly applied to streamflow, is entirely adequate to maintain the discharge at about 36 cubic feet per acre per day. This is above the average low-water discharge, so that the seemingly insignificant amount of rainfall that sufficies to maintain the stream in customary flow must be clearly recognized.

(2) The water comprised in surface flow is of importance only in heavy or infrequent substantial rains. Its effects are always apparent in streamflow diagrams during the rainy season of the summer. As previously stated, a few days of rainless weather more or less completely exhausts the R_2 portion, but when rainy days follow each other at short intervals the features in the discharge diagrams due to surface flow can hardly be segregated from effects which properly belong to the R_3 portion.

A careful analysis of the so-called excess discharge resulting from summer rains, on the watersheds of this study, shows that in ordinary cases the increased discharge from water which reaches the streams almost directly through surface flow is of short duration and small amount. Observations over the watersheds show that there has been in the past practically no such phenomena as surface run-off from the main slopes of the watersheds. Quantitative analysis of this excess discharge in both streams indicates that it is only the water falling in the streams, and on the moist ground within a few feet of them, which temporarily augments their flow.

Directly related to this, and bearing on the next subject, ground water, is the fact that even considerable amounts of rain late in the summer do not have more than a temporary influence on streamflow. In short, the steady flow declines during the summer, even when monthly precipitation is greater than streamflow. If the water does not run off on the surface, and does not soak in, to augment the ground water, what does become of it? It seems fairly evident that in this particular case, though most of the rain water soaks into the soil, it should be considered as intercepted water, R_1. Both the immediate surface of the soil, consisting of litter and humus, and a shallow zone of the mineral soil which is very fully occupied by tree roots, become, through surface evaporation and transpiration in the very dry atmosphere of this region, extremely arid. This is especially the case where aspen occupies the ground very fully, this species being a more extravagant user of water than conifers, and not inclined to root deeply. As a result, this surface layer, except with very unusual rains, never becomes thoroughly wetted after drying out in the spring, and such water as it holds from time to time establishes no capillary connection with the true ground water.

(3) The main phenomena of flow, especially when not complicated and dominated by the more or less immediate consequences of recent substantial rains, are related chiefly to the more or less permanent but variable water content of the watershed, supplemented, or rather augmented, as that content is from time to time, by rainfall contributions, and depleted hourly and daily by the two processes of stream discharge in the one case and evaporation and transpiration in the other.

The fundamental problem is to give full account of the disposal of the entire 100 per cent of rainfall so as to apportion the totals among the several ways in which it is disposed of.

In the case of snowfall, representing, as before stated, about 50 per cent of the total precipitation, different conditions obtain. Snow begins to fall in appreciable amounts about the middle of October, although the occurrence of very considerable amounts of snow in September is not infrequent, especially in the higher altitudes. All of the September snow and the greater part of the early October snow disappears by melting and vaporation, and while a relatively small amount reaches the streams, the greater portion must serve to replenish evaporation losses and to augment ground water. The disposition of the snow water is greatly complicated by both altitude and slope. It should be remembered that there is a difference of about 1,900 feet between the extreme upper and lower portions of the watersheds. Snow comes earlier and lasts longer in the higher altitudes and disappears quickly on the lower south slopes. The north slopes are permanently covered with snow on the average by October 31, the south slopes not until 41 days later, or on December 11. Snow which falls on the south slopes before the date on which the snow becomes permanent for the winter, and also snow which falls after the snow disappears at the close of the melting season in spring, quickly disappear and must be considered as serving in the main to augment ground water.

The interception of snow by trees and vegetation is small as compared with rain, because, in the main, the coniferous area only is effective in preventing the snow from reaching the soil. The stand of conifers is not dense enough to prevent snow from reaching the ground, except over an area equal to the spread of the foliage at its greatest diameter. There will be, of course, less snow directly under the larger conifers, but in the aspen area there is believed to be very little interception.

The melting of the snow cover is very largely controlled by slope and air temperature. On south slopes melting begins and is practically concluded, except at the higher altitudes, before it is fairly started on north and east slopes. There is apparently little surface run-off on the lower south slopes; on the upper south slopes the appearance of springs along the channel of the stream is positive evidence that south slopes contribute largely to streamflow; the flow, however, is underground rather than surface.

It may be expected, therefore, that, although the total snowfall on the average is not any greater than the rainfall, a considerably greater portion of it percolates into the deeper soil and is later effective in maintaining streamflow.

Attempt has been made to dispose of the precipitation measured on the A watershed in accordance with the previous analysis. The results appear in Table 24.

TABLE 24.—*Disposition of precipitation, watershed A. Precipitation and run-off observed; interception, transpiration, and evaporation computed.*

Year.	(1) Precipitation.	(2) Run-off.	(3) Interception.	(4) Transpiration.	(5) Evaporation.
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1912	21.30	8.368	3.61	3.92	5.402
1913	18.63	4.778	3.84	4.14	5.872
1914	22.64	5.629	4.28	4.74	7.991
1915	19.97	5.354	2.59	3.04	8.986
1916	22.71	5.596	4.10	4.28	8.734
1917	22.88	9.644	2.66	2.73	7.846
1918	18.90	3.196	4.28	4.52	6.904
Mean	21.00	6.081	3.62	3.91	7.389
Percentage	....	29.0	17.0	18.0	36.0

The data in the columns headed "Precipitation" and "Run-off," respectively, were observed; those in the columns headed "Interception" and "Transpiration," respectively, were computed; and finally the column headed "Evaporation" is the difference between the sum of columns 2, 3, and 4 and the figures of column 1. In other words, after diminishing the precipitation by the run-off plus the interception plus the transpiration, the remainder is assumed to represent the loss by evaporation. Inasmuch as run-off, interception, transpiration, and evaporation total 100 per cent and the precipitation is thus completely disposed of, it is obvious that the computed values are inexact unless it be assumed, as it may be without serious error, that the quantity of water in the watershed was the same in the beginning of the year as at the end. As a matter of fact, this amount may vary somewhat from year to year. It is never very large, except as a result of heavy or continued rains. The disposition of the precipitation is graphically presented in figure 19.

On page 27 it is shown that the average discharge on October 1 for the seven years beginning with 1911 is 0.0104 inch for A and 0.0102 inch for B. For the week ending October 1 it is 0.0097 for A and 0.0098 inch for B. The average low-water discharge of the year is found in the second week of February, when A reaches the low average daily value of 0.0076 and B 0.0093 inch over watershed. During this period, October 1 to, say, February 25, the only water reaching the stream is from underground water and the small increment from snow melting on warm days. As before stated, practically all of the snow for September and the first half of October melts and may be effective in maintaining streamflow later, or may disappear much as does the larger part of summer showers.

The total contribution from melted snow must be, in the nature of the case, quite small, hence it is argued that ground-water contributes the larger share of winter streamflow.

Interception of rain by trees.—It is well known that a certain quantity of rain or snow is intercepted by trees, shrubs, and other forms of vegetable cover and never reaches the soil. The amount of rain thus intercepted in a forest must depend primarily upon a number of conditions, viz, the character of the trees, their age, density

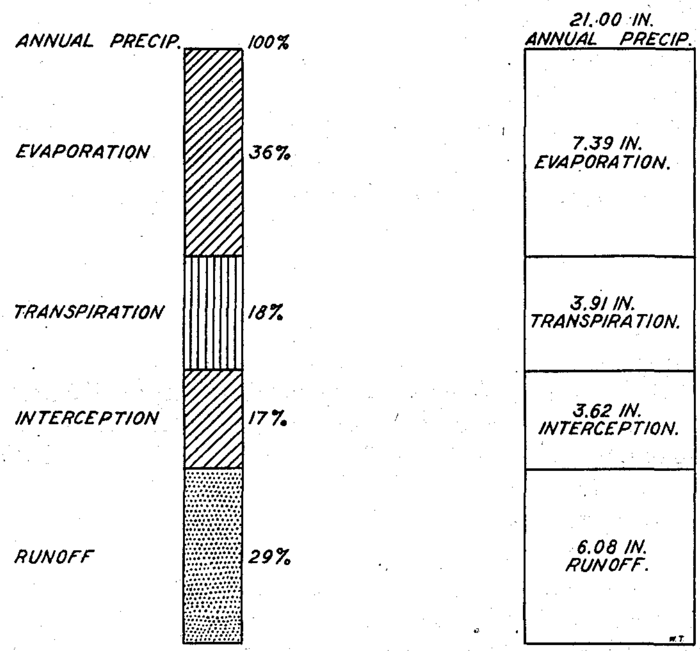

FIG. 19. Disposition of precipitation.

of crown, density of stand, the intensity of the snow (whether dry or moist), also the velocity of the wind during precipitation, etc.

Many experiments looking to a determination of the amount of precipitation intercepted by trees have been carried out in various parts of the world. The estimates differ, as might be expected. Zon,[2] in summing up the results of European investigations, says:

> As a result of a great number of investigations it may be assumed that coniferous forests intercept more precipitation than broadleaf forests. Under average conditions a spruce forest will intercept about 39 per cent of the precipitation, a broadleaf forest about 13 per cent. The amount of precipitation intercepted is the smallest in a young stand and greatest in a middle-aged one.

In a search for further definite quantitative results, the work of Dr. H. E. Hamberg [3] on the influence of forests upon the climate of Sweden was examined. The following is a summary of Dr. Hamberg's results:

Rainfall measurements made in a clearing and at three places within an adjoining forest, the first under a thick

[2] Final report United States Waterways Commission, p. 229.

[3] Hamberg, H. E., De l'influence des forêts sur le climat de la Suède. Stockholm, 1885.

stand of pines 80 years old, the second in an old forest with a sparse stand of pines, and the third in a young forest of firs, gave the following amounts expressed as a percentage of precipitation measured in the clearing. The year was divided into two parts, May to October and November to April.

In the first or warm season the raingage in the dense forest of old pines caught but 69 per cent of the precipitation in the clearing. In the winter half-year it caught 80 per cent. In the old forest with a sparse stand of pines the rain-gage caught 98 and 106 per cent, respectively, of the amount caught in the clearing, and in the forest of young firs the catch was 68 and 86 per cent, respectively. Somewhat similar results were obtained at two other places, but they were not considered sufficient to furnish positive conclusions as to the quantity of water which on the whole reaches the soil in a forest. Finally, a special study extending from November, 1886, to June, 1900, was made near Hjorthagen. In this experiment the different raingages were arranged as follows: A mast was erected in a small clearing, with its top on a level with the tops of the trees and rain-gage No. 1 was placed on the top of the mast. No. 2 was exposed in a bare clearing protected from the winds. No. 3 was in a still smaller protected clearing at the foot of the mast. The other exposures were chosen with regard to the thickness of the foliage in tops and branches of the neighboring firs. At gages Nos. 5, 6, and 7, the branches of two or more trees touched each other. The remaining gages were placed either under the trees at different distances from the trunks or under the extreme ends of the branches

For the purpose of comparison, the amounts of water that fell in the different months of the year, expressed as percentage of the catch on the top of the mast, are given in Table 25.

TABLE 25.—*Percentage of rain at different stations at Hjorthagen.*

	The mast	Clearings.		Under the trees or at the extremity of the branches.									
	1	2[1]	3[2]	4[3]	5[2]	6[4]	7[2]	8[3]	9[1]	10[5]	11[5]	12[5]
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
January	100	97	82	77	91	61	60	57	53	72	110	64
February	100	94	93	80	48	60	42	50	50	37	36	40
March	100	95	89	91	78	60	64	44	44	42	56	41
April	100	94	91	71	96	74	80	35	59	66	49	43
May	100	106	105	92	95	93	95	88	58	14	13	8
June	100	101	100	78	75	97	68	83	69	70	53	40
July	100	101	.....	76	.....	89	.....	76	62	62	37	45
August	100	103	.....	84	.....	92	.....	86	51	24	11	11
September	100	101	.....	96	.....	82	.....	86	59	53	26	31
October	100	100	.....	90	.....	82	.....	77	40	30	32	21
November	100	100	94	106	62	57	60	44	47	33	35	18
December	100	97	82	78	55	44	30	47	46	39	50	40
May-October	100	101	.....	84	.....	88	.....	81	58	48	32	30
November-April	100	95	88	82	84	63	66	47	45	47	53	40
The year	100	99	.....	84	.....	80	.....	70	53	47	41	34

[1] November, 1886, to September, 1889.
[2] November, 1889, to June, 1890.
[3] November, 1888, to October, 1889.
[4] November, 1888, to June, 1890.
[5] November, 1886, to October, 1888.

Dr. Hamberg concludes that nowhere and in no one month is more precipitation measured in the forest than in the clearing. In the most sheltered spots under the trees there reaches the soil in summer only 30 to 32 per cent and in winter only 40 to 53 per cent of the quantity of water that is measured at the tops of the trees or in the clearings. The forest of firs at this station, as at Alderstugan and Sparhult, permits the rain to pass more freely than the snow; thus, for example, the quantity measured at station No. 6 for the period May to October is 88 per cent, but for the period November to April only 63 per cent, while at station No. 8 the difference is still greater, varying from 81 to 47 per cent, respectively.

The amount of rain which reaches the soil in wooded regions depends, then, upon the density of the forest; in a dense forest, especially in one in which there is a growth of underbrush, this quantity amounts to one-half of the total quantity.

The author further remarks "that the greater the precipitation the greater the amount which reaches the ground, thus, for example, at station No. 12 of Table 25, considering all of the amounts less than 5 mm., but 7 per cent reaches the ground. For rains between 5 and 9.9 mm. the percentage rises to 22, and for those rains in excess of 10 mm. the percentages rise to 50. A similar well-marked and consistent relation with even greater values holds for the other stations."

Another writer on the subject[3] holds that as much as 40 per cent of precipitation is intercepted in a 20-year stand of spruce.

The danger and difficulty of applying to the Wagon Wheel Gap area the results hereinbefore quoted lie in the fact that the forest cover of that area is not uniform. In the cold months, as before intimated, the aspen intercepts very little snow; on the other hand, conifers, besides preventing the snow from reaching the ground under them, at times catch and hold in the foliage considerable quantities of snow, a large part of which is sooner or later evaporated. The stand of conifers, as a rule, is not sufficiently close to prevent snow from reaching the ground in the open spots throughout the areas in which these trees predominate. The question, then, is what portion of the coniferous areas is shielded from snow? In answer to this an opinion based on personal visits to the area in the cold season is offered, viz, that the equivalent of 0.03 inch of precipitation in the form of snow is intercepted for each snowstorm over not more than one-tenth of the known coniferous area, which on B is 53 acres. Assuming 60 acres of conifers in A, there is a total of 113 acres on both watersheds, or 27 per cent of the total area.

For tentative purposes it is estimated that the area directly under the conifers is about one-tenth of the coniferous area; therefore but one-tenth of the total area is shielded by the trees. (See Mr. Jarboe's comment, p. 35.)

In computing the amount of precipitation intercepted in the Wagon Wheel Gap area, as in the case of transpiration, two independent calculations were made, by

[3] Edouard Hoppe: Regenergiebigkeit unter Fichtenjungwuchs (Mitteilung der K. K. forstlichen Versuchsanstalt in Mariabrunn Wien, 1902).

what may be designated as the X and Y methods. In the X method for computing interception, each separate rain during the season of summer rains was reduced by 0.03 inch; in case there were two or more showers during daylight hours, separated by an interval of at least two hours without rain, 0.03 inch was subtracted for each shower and no distinction was made as to timber distribution or surface cover, it being assumed that the amount chosen for each shower, 0.03 inch, would very closely approximate the average interception for the whole area.

All of the light rains up to and including 0.03 inch were considered as being totally intercepted; accordingly, the total interception is made up of these light rains and 0.03 inch of each rain greater than 0.04 inch as above.

About 13 per cent of B is not forested, and perhaps as much as 15 or 18 per cent of A is without forest cover.

In the cold season, when precipitation is in the form of snow, the conditions as to interception are decidedly different. A considerable portion of the snowfall in the Rocky Mountain region, especially during the colder months, is dry; hence very little of it is intercepted by deciduous trees and only a minimum amount by conifers. However, with a rise in air temperature during spring the snowfall in the majority of cases is moist and the maximum interception by conifers is probable. A count of 759 snowfalls by months gives the results shown in Table 26.

TABLE 26.—*Character of snow storms at Wagon Wheel Gap, Colorado.*

	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	Total.
Dry	3	19	44	91	79	83	77	41	26	.....	463
Wet	8	33	18	3	17	19	45	85	55	13	288

In computing the amount of snow intercepted by the forested area, the following considerations have been kept in mind:

First, for reasons already stated, the coniferous area only will intercept snow—a small amount in the case of dry snow, more in the case of moist snow—but only the area directly under the trees will be affected. The stand of conifers is not close enough to shield completely the total area over which these trees predominate.

Second: Granting the foregoing, it is assumed that the area directly under the conifers is to the whole area of conifers as 1 : 10,[4] and since the total coniferous area on both watersheds does not exceed 27 per cent, it follows that only one-tenth of 27 per cent of the estimated interception over the entire area may be used to represent the actual loss by interception.

The plan followed in arriving at the total incerception during the season of snow was, first, to sum the daily amounts equal to or less than 0.03 inch, which sum was considered as being wholly intercepted; second, to deduct 0.03 inch from each 24-hour precipitation of snow in excess of 0.03 inch, and to set aside as wholly intercepted 2.7 per cent of this sum, which, being added to the snowstorms of 0.03 inch or less, gave the total interception of snow.

The amount of snow intercepted in storms amounting to more than 0.03 inch, according to the foregoing, is very small and remarkably uniform, ranging from 0.04 to 0.06 inch per season. While this amount seems unusually small, it should be remembered that the snow in a great majority of the snowstorms in winter is dry and does not cling to the conifers. Moist snow in April, May, and June, of course, lodges more or less in the foliage of conifers, and since the mean air temperature passes above 32° in April, there must be more or less melting of the lodged snow on that side of the tree exposed to the direct rays of the sun. As melting continues portions of the lodged snow become loose and fall to the ground. A portion of the lodged snow evaporates, but no method is known of evaluating the quantity which is evaporated.

It is proper to add in this connection the results of a short series of careful observations made during the summer of 1919 in Washington, D. C., bearing upon the amount of rainfall required to wet the foliage of a tree so that the leaves will begin to shed water in an appreciable quantity. The tipping-bucket raingage exposed on the roof of the Weather Bureau building served to record the depth and intensity of the rainfall and the maple trees on both M and Twenty-fourth Streets, immediately adjoining, were used to observe the interception due to that species of tree.

An observation consisted in noting the time at which rain began to penetrate the foliage and reach the pavement. It was found, as might have been expected, that young trees began to shed rain before the older ones, and finally one tree was found, a mature maple about 35 feet high, whose foliage prevented rain from passing through it until at least 0.03 inch had been recorded by the tipping-bucket gage in the Weather Bureau building, and then the amount which reached the ground was considerably below that which was reaching the ground outside of the area protected by the tree. When the rain begins at an excessive rate, however, the ground under the tree may be wetted with as much as 0.02 inch, and the rate of fall through the foliage is greatly increased over that in moderate rains. The rains in the Wagon Wheel Gap area very rarely, if ever, fall at an excessive rate, such as frequently occurs in the humid regions of the east and south.

Method.—Method Y proceeds in this wise: Giving consideration to the results obtained by European investigations, many of which under favorable conditions indicate an interception of from 40 to 50 per cent of the precipitation, it was the object to arrive at an amount greater than that already reported under method X, which barely reaches 10 per cent of the annual amount. Repeated trials and varying estimates resulted in selecting the value of 0.07 inch interception for conifers and 0.04

[4] Mr. J. H. Jarboe is of opinion that 1: 6 is more accurate.

inch for deciduous trees; the mean of these, computed with regard to the area occupied by each species of tree, is 0.0498, or, roughly, 0.05 inch.

Each 24-hour rainfall of that amount or less was considered as being intercepted, and the total of these amounts was taken from the record of 24-hour precipitation by watersheds. Reference was then had to the hourly automatic records for the D station. This station was considered more appropriate than the C record at a lower altitude and outside the boundaries of the experimental watersheds. The differences between the two records, except for such as are contingent upon local variation in the horizontal distribution of precipitation, are not great.

From each hourly precipitation of as much as 0.06 inch the sum of 0.05 was uniformly deducted. In cases where the rainfall was in consecutive hours this procedure eliminated as much as 45 per cent, on the average, of the total. It seems probable that in individual cases this amount is too great, but, on the other hand, the interception from light hourly rainfalls may be too small.

The number of storms in which rainfall exceeding 0.05 inch an hour occurred for several consecutive hours is shown in Table 27; also the percentage of rain deducted for those particular storms.

TABLE 27.

Year.	Number of storms.	Percentage deducted.	Year.	Number of storms.	Percentage deducted.
		Per cent.			*Per cent.*
1912	7	43	1917	4	51
1913	10	57	1918	14	41
1914	8	43			
1915	9	42	Average	9	45
1916	14	39			

We have already intimated that, in individual cases, this method is at variance with the fact that in heavy rains the surface of the foliage soon becomes wetted and thereafter sheds rain freely.

In winter the amount of interception is difficult of determination, since we have no hourly records of precipitation during the winter season. All precipitation of 0.05 inch or less per day plus the sums of 0.05 from each daily precipitation above that amount were used, considering only 27 per cent of the entire area covered with conifers. This furnished small amounts, and is probably not much in error. The total amounts for each season are given in Table 28, in which will be found for comparative purposes the total seasonal interception by the X method. The mean of the two watersheds has been used in Table 28.

TABLE 28.—*Interception by trees.*

[Inches and hundredths.]

Year.	1912	1913	1914	1915	1916	1917	1918	Mean.	Per cent annual mean.
Method X	1.83	2.07	2.57	1.25	1.88	1.48	2.10	1.88	9
Method Y	5.39	5.61	5.98	3.93	6.33	3.84	6.46	5.37	25
Mean	3.61	3.84	4.28	2.59	4.10	2.66	4.28	3.62	....

NOTE.

J. H. JARBOE, Meteorologist in charge.

[Wagon Wheel Gap station. Dated August 21, 1919.]

On watershed B there are more than 5,000 conifers between 6 and 30 inches in diameter. Assuming that the crown spread of these trees will average 10 feet, and this is a conservative estimate, we have a shielded area of about 9 acres. This is about one-sixth of the area covered by conifers. It would seem that the area of one-tenth is perhaps too low.

It is true that dry snow rebounds and sifts through the crowns of the conifers to a certain extent, but where little wind movement accompanies the snowfall, as is the general condition at Wagon Wheel Gap, the snow, even though dry, collects on the trees in large quantities and is held up for a long period unless heavy winds follow the snowfall.

Snow mats, one in the open and two under conifers, were used at this station between March 7 and April 9 of this year. Daily observations of snowfall on these mats were taken. Any snow that afterwards fell from the trees was also measured. The total snowfall on the mat in the open was 30.2 inches and a mean of the amounts that fell on the mats under the conifers was 12.3 inches. Most of the snowfalls, however, were moist and conditions were favorable for a maximum interception by the trees.

It would seem that more precipitation is intercepted by trees than is shown by the X method. After observing daily all the snowfalls at Wagon Wheel Gap for a period of two years it is believed that measurement will show that more than 0.03 inch of melted snow is intercepted, even during dry snow storms. Table 29 shows a larger interception, but the observations are for short periods and of course for that reason can be given little weight.

TABLE 29.—*Snowfall intercepted at Wagon Wheel Gap—Amounts caught.*

1919	Timber.		Open.		1919	Timber.		Open.	
	Mat No. 1.	Mat No. 2.	Inches.	Water Con.		Mat No. 1.	Mat No. 2.	Inches.	Water Con.
Mar. 7	0.1	0.1	0.1	0.01	Mar. 24	1.4	1.3	3.5	.26
8	.3	.3	.7	.06	28	T.	T.	.2	.01
9	T.	T.	.1	.01	29	.4	.4	1.4	.22
10	.5	.5	1.3	.09	31	.2	.2	.4	.02
11	T.	T.	.1	.01	Apr. 2	T.	T.	.1	.01
14	.4	.4	.9	.08	7	2.3	2.4	4.6	.18
21	2.0	2.0	5.7	.55	8	.8	.8	1.7	.10
22	3.7	3.7	9.2	.84					
23	.2	.2	.2	.06	Total	12.3	12.3	30.2	....

Rain intercepted by trees at Wagon Wheel Gap—Gage catch.

	Fir.	Aspen.	Open.		Fir.	Aspen.	Open.
July 13	0.37	0.45	0.64	Aug. 1	0.03	0.13	0.19
14	.04	.20	.33	2	T.	.01	.06
15	.21	.47	.54	3	T.	.01	.06
16	.37	.65	.71	4	T.	T.	.02
17	.01	.02	.08	9	T.	T.	.02
19	0	T.	.04	10	0	0	.02
20	.04	.14	.22	11	.01	.06	.08
26	T.	.02	.08	15	T.	.06	.15
28	T.	T.	.01	19	T.	.01	.05
29	T.	.06	.12				
30	T.	T.	.02	Total	.04	.28	.65
31	T.	.02	.11	Per cent	6	43	....
Sum	1.04	2.03	2.90				
Per cent	36	70	....				

Method Y would seem to eliminate too large an amount of precipitation. It would seem to be in error to deduct 0.05 inch from each hour of consecutive hourly precipitation, for after rain has fallen for several hours the amount intercepted by the trees becomes less and less until it is, for all practical purposes, just a matter of the amount evaporated in the crown of the trees.

TRANSPIRATION.

Meyer[5] recommends the use of the following values for tentative purposes in the calculation of normal seasonal transpiration:

For grasses and agricultural crops, 9 to 10 inches.

For deciduous trees, 8 to 12 inches.

For small trees and brush, 6 to 8 inches.

For coniferous trees, 4 to 6 inches.

A very great amount of work has been done on the general subject of transpiration, most of which, however, has been confined to field crops and greenhouse plants that can be potted and kept under artificial control.

Attempts to compute the transpiration of a tree from experiments made on the leaves of a small branch and extending the results to an entire forest do not give results which inspire great confidence. It is perfectly feasible, as shown by Briggs and Shantz[1] to determine the water requirements of certain field crops under controlled conditions and to extend the results of the experimental work to the determination of the water requirement of crops in the field. The amount of water transpired by a forest, however, is not easily determined, although various estimates have been made. These range from a minimum of 0.002 to 0.021 inch per day. Calculations based on the dry weight of the leaves on a single tree have shown the tremendous possibilities of transpiration, and when the results are multiplied by 500 or 1,000, as the case may be, to represent the transpiration on an acre of forest trees, it frequently results in making the transpiration greater than the annual precipitation. Meyer[6] has well said:

> If plants, under field conditions, transpired a quantity of water equal to from one-half to two times the evaporation from an equivalent surface of water, as claimed by some experimenters, a great many streams in the United States, that have a very appreciable sustained flow, would become intermittent, because there would be no ground water to supply them.

The monthly and seasonal transpiration for the Wagon Wheel Gap area have been computed by two more or less independent methods, which, for purposes of discussion, will be referred to as X and Y. Each method will be described in detail, beginning with method X.

Method X.—The following considerations have led to a modification of the limiting values given in the beginning of this section. First, the season at Wagon Wheel Gap, owing to the altitude, is short. The daily mean temperature passes above 43° F. about May 24 and recedes to that amount on September 28, thus making a season of 127 days. At Denver, Colo., the season is 220 days in length. Second, the character and density of vegetation in the experimental area. The stand of aspen is not uniform, varying from thin to dense. The stand of conifers is on the average rather sparse, except for small clusters here and there. The grass covering is also light everywhere, except in the small irrigated area in the camp, which is outside of the experimental area; and, finally, the sunshine during the season of transpiration is not abundant. Moreover, a large part of the area is in the shadow of the mountain from about 3.30 p. m. to sunset.

It seems that a reduction of at least 18 per cent should be made for the shortness of the season and that an additional reduction of, say, 10 per cent on account of deficient sunshine is warranted. In connection with deficient sunshine the fact has been taken into consideration that owing to the altitude the station is frequently within the lower cloud level and that during such periods more or less moisture is condensed upon the foliage in the forest, thus diminishing for the time being the opportunity for transpiration. If, now, the mean of Meyer's limiting values (10 inches for deciduous trees and 5 inches for conifers) is taken and reduced by 28 per cent, the result for use as a working basis is a seasonal transpiration of 7.2 inches for deciduous trees and 3.6 inches for conifers. The grass area may be neglected.

These basic values are further modified by a consideration of the rainfall of the three summer months and the first half of September—107 days—as follows: The sum of the current rainfall for May and June is compared with the mean rainfall for those months during the eight years of the experiment. If the current rainfall is the same as the average it is considered that transpiration will be average; if rainfall has been below average, it is considered that transpiration will also be below average in direct proportion, and likewise when rainfall is above average transpiration will be above average. In practice the rainfall of the month preceding and the current month were combined and compared with the eight-year average for the same months. In order to make allowance for the nonforested area a further reduction of 17 per cent was made, since the combined aspen and coniferous areas aggregate 83 per cent of the total area on B and it is assumed that these relations hold for A.

Method Y.—In the compilation for method Y the following values were used: For transpiration from aspens 0.11 inch per day, under most favorable conditions of sunshine, etc.; for transpiration from evergreens 0.07 inch per day; aspens 120 acres, evergreens 50 acres, mean value 0.098 inch per day.

Dr. MacDougal[7] states that an acre of beech trees containing 400 to 600 specimens will transpire about 2,000,000 pounds in a single summer. The length of the summer and other physical data are not given, hence the possibility of an error in our interpretation. A single summer has been taken as 92 days, wherefore, converting transpiration in pounds to daily amounts and expressing

[5] Elements of Hydrology, p. 262.

[6] Loc. cit., p. 260.

[7] D. T. MacDougal, Encyclopedia of Horticulture, Vol. VI, p. 3365.

the result in inches, the values above stated are obtained. In determining the transpiration from conifers the value given by Meyer[8] was used without modification as in method X.

The mean value 0.098 inch (roughly 0.10 inch) per day served as a basis for computing monthly and seasonal transpiration. The computations were made as follows: It was considered that on a day with 100 per cent of sunshine and 0.10 inch of available water, full transpiration would occur. The period of transpiration was taken as that during which aspens are in leaf, from June 8 to September 18, 103 days; therefore, $103 \times 0.10 = 10.30$ inches for the normal seasonal precipitation. The eight-year average precipitation used in method X is about an inch less.

The prevailing sunshine was taken from the automatic records of Station C; applying a correction based on the duration of sunshine and multiplying the values so determined by $\frac{\text{"seasons rainfall"}}{10.30}$ the final values are obtained.

TABLE 30.—*Computed transpiration in inches.*

	1912	1913	1914	1915	1916	1917	1918	Mean.
Method X	4.71	5.09	6.18	3.29	4.16	3.24	4.50	4.45
Method Y	3.12	3.20	3.30	2.79	4.40	2.22	4.55	3.37
Mean	3.92	4.14	4.74	3.04	4.28	2.73	4.52	3.91

It is thus possible, using nearly the same basic values, to obtain different results. It is not claimed that either of the annual amounts represents the absolute quantity of water lost to streamflow by transpiration, but it is believed that they are not far wide of the mark.

Y is smaller than X mainly because both the rainfall and sunshine factors used in the computations tend to give smaller values than were given by method X. Another reason is that the length of the season in method X was taken, as a matter of convenience in the computations, as from June 1 to September 15, a period of 107 days, as against 103 days in Y. The mean of the two computations was used in Table 24.

CHARACTERISTIC DIFFERENCES IN STREAMFLOW OF WATERSHEDS A AND B.

A casual inspection of the records of streamflow shows at once that the régime of stream A is different from that of stream B in several particulars.

It was observed in the beginning, and has been repeatedly confirmed by subsequent observations, that the run-off due to surface flow—that portion of the rainfall previously classed as R_1—is greater on A than on B. Contrary to first impressions, it requires about an hour longer on the average for the maximum volume of such water to reach the dam; that is to say, the surface flow of B crests anout an hour earlier than of A. On the other hand, the run-off due to underground waters, R_3, at times is considerably greater on B than on A, and naturally the maximum volume of flow, unit areas considered, reaches its crest later on B than on A. In other words, Watershed B is a greater conserver of precipitation than A.

The lag in run-off of stream B.—The evidence of the lag in run-off of stream B is so voluminous that it is difficult to make a selection. The only great rain flood thus far experienced, on October 4–5, 1911, shows that, while the surface flow from each watershed crested about the same hour on October 5, the discharge of stream A diminished rather steadily thereafter. Stream B discharged a less volume from the surface flow, but the hourly discharge held up and actually increased, reaching a maximum at 2 p. m. of the 9th, four days after the primary crest from surface runoff. The facts are graphically portrayed in figure 20. From the behavior of B with

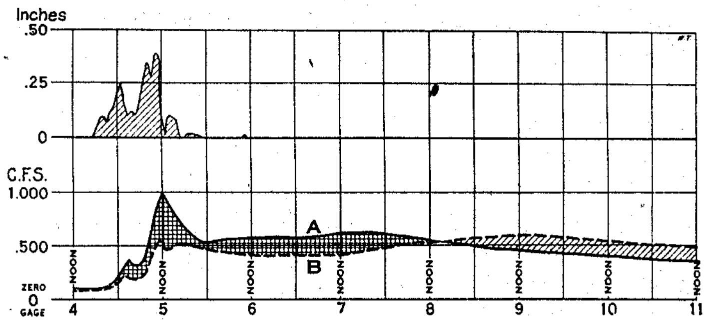

FIG. 20. Hourly rainfall at D and streamflow, A and B, October flood of 1911.

respect to A in the matter of run-off not only from rain but also from snow, the important inference is drawn that the capacity for storage of underground water on B is greater than that on A.

The statement that the run-off from surface flow on B reaches stream B about an hour earlier than on stream A is based on a study of 42 cases of sharp rises due to the most intense rains which fall over the area. In this study it was shown that on an average stream A rose from low water to a crest within four hours, while on stream B the crest was reached within three hours. The time of beginning of precipitation did not always coincide with the hour of low water, hence great refinement in arriving at this result was not possible.

Run-off from snow.—The run-off from melting snow must reach the stream largely through underground channels. When snow melts slowly the opportunity for percolation into the soil is very great, and, as in the case of rain, any surface run-off of consequence would not be expected, except at the time of maximum melting, when the surface run-off from north slopes is probably greater than ever happens in the case of rainfall. Snow begins

[8] Loc. cit.

to melt on south slopes in February. The resulting water, however, does not quickly become available for streamflow or even to replenish ground water, since the water percolates first into the snow cover itself and does not reach the soil until at a later stage in the cycle of melting. The explanation of the disappearance of the snow on the lower south slopes without apparently increasing streamflow has been more or less of a puzzle. Very early in the experiment it was noticed, as was to have been expected, that the snow disappeared much earlier on the south than on the north slopes but there was no immediate response in streamflow.

On further consideration, it would appear that the early snow melting on the south slopes can not be expected to appear quickly as run-off, since, as before remarked the water from the superficial layers must percolate into the snow cover and therefore does not reach the soil or flow away over the surface as in the case of rain.

Experiments by Horton[9] show that under suitable conditions snow behaves like any other permeable medium, such as porous soil, as regards the percolation of water through it and capillary retention of water in the interstices of the medium.

One of the writers, while at Wagon Wheel Gap in April, 1919, using permanganate of potash as a stain, made several simple tests in the cover of old snow, which at that time ranged in depth from 24 to 34 inches and had a density of about 30 per cent. The procedure was very simple; that is to spread a few grains of permanganate on the surface of the snow and subsequently to uncover a cross-section of the snow layer immediately adjoining and observe the depth and extent of the penetration of the stain. Of course, the crystals of permanganate being opaque, there was greater melting in their immediate vicinity than elsewhere, but it is not believed that the circumstance vitiates the accuracy of the conclusions. It was found that surface snow water penetrated to the ground through a snow layer of 32.5 inches in depth in 24 hours and also spread laterally 15 inches from the vertical in the direction of the slope in the same time. The conclusion reached from the tests was that the flow of water from surface snow melting is determined by gravity and its speed is conditioned upon the porosity of the snow directly underneath, thus confirming the results reached by Horton in a different way.

The total area of south slopes is less than a third of the watersheds.

In order to examine the data in greater detail, the daily observations of temperature and run-off have been tabulated for both watersheds for the month of February and first half of March, 1916 (Table 31). This tabulation seems to give a close-up view of the beginning of the snow melting when the mean temperature is yet considerably below the melting point.

[9] The Melting of Snow. Robt. E. Horton, MONTHLY WEATHER REVIEW, 43:599.

TABLE 31.—*Relation between temperature and run-off.*[1]

1916.	Daily mean temperature (°F.).		Hour (degrees above 32).		Excess in day (degrees).		Run-off in inches over watershed.		24-hour change (inches over watershed).		Changes in run-off (cubic feet per acre).	
	A.	B.	A.	B.	A.	B.	A.	B.	A.	B.	A.	B.
Feb. 1	−8	−10	0	0	0.00	0.00	0.0068	0.0084	−0.0001	−0.0001	−0.2	−0.3
2	1	0	0	0	0.00	0.00	.0068	.0084	0	0	.0	.0
3	18	17	0	0	0.00	0.00	.0068	.0085	0	+1	−0.2	+0.2
4	20	21	0	0	0.00	0.00	.0068	.0085	0	0	+0.2	+0.2
5	22	22	0	0	0.00	0.00	.0068	.0085	0	0	.0	−0.1
6	24	23	23	16	0.96	0.67	.0068	.0084	0	−1	−0.3	−0.3
7	26	25	39	32	1.62	1.33	.0068	.0085	0	+1	.0	+0.3
8	29	29	28	26	1.17	1.08	.0068	.0085	0	0	+0.3	.0
9	27	27	44	42	1.83	1.75	.0068	.0085	0	0	−0.3	−0.2
10	24	23	9	2	0.37	0.08	.0068	.0085	0	0	+0.3	+0.1
11	27	26	46	42	1.92	1.75	.0069	.0086	+1	+1	+0.3	+0.3
12	21	20	0	0	0.00	0.00	.0070	.0086	+1	0	+0.3	.0
13	18	16	3	0	0.12	0.00	.0070	.0086	0	0	.0	−0.1
14	22	21	24	11	1.00	0.46	.0070	.0084	0	−2	.0	−0.4
15	22	21	0	0	0.00	0.00	.0072	.0085	+2	+1	+0.5	+0.2
16	20	18	0	0	0.00	0.00	.0074	.0085	+2	0	+0.9	.0
17	21	20	7	2	0.29	0.08	.0076	.0085	+2	0	+0.8	+0.1
18	22	22	3	3	0.12	0.12	.0077	.0086	+1	+1	+0.4	+0.3
19	20	18	0	0	0.00	0.00	.0078	.0086	+1	0	+0.2	−0.1
20	20	19	5	0	0.21	0.00	.0077	.0085	−1	−1	−0.2	−0.2
21	21	21	6	5	0.25	0.21	.0075	.0086	−2	+1	−0.7	+0.1
22	25	26	2	0	0.08	0.00	.0073	.0086	−2	0	−1.0	+0.2
23	19	19	1	0	0.04	0.00	.0073	.0086	0	0	.0	−0.1
24	21	20	12	8	0.50	0.33	.0072	.0086	−1	0	−0.2	.0
25	22	21	16	11	0.67	0.46	.0071	.0086	−1	0	−0.4	+0.1
26	23	23	16	17	0.67	0.71	.0072	.0086	+1	0	+0.3	+0.1
27	27	28	6	8	0.25	0.33	.0072	.0087	0	+1	+0.1	+0.2
28	22	22	0	0	0.00	0.00	.0071	.0088	−1	+1	−0.4	+0.3
29	17	17	0	0	0.00	0.00	.0071	.0087	0	−1	−0.1	−0.3
Mar. 1	19	19	0	0	0.00	0.00	.0070	.0089	−1	+2	−0.1	+0.6
2	13	12	0	0	0.00	0.00	.0069	.0087	−1	−2	−0.6	−0.5
3	14	13	0	0	0.00	0.00	.0068	.0086	−1	−1	−0.4	−0.5
4	31	30	56	54	2.33	2.25	.0070	.0087	+2	+1	+1.0	+0.5
5	31	31	18	16	0.75	0.67	.0071	.0088	+1	+1	+0.2	+0.3
6	21	21	0	0	0.00	0.00	.0071	.0089	0	+1	−0.1	+0.3
7	29	29	25	23	1.04	0.96	.0071	.0089	0	0	.0	+0.1
8	39	38	174	162	7.25	6.75	.0082	.0095	+11	+6	+4.3	+2.0
9	42	42	236	244	9.83	10.17	.0102	.0108	+20	+13	+7.1	+4.7
10	38	38	153	157	6.38	6.54	.0116	.0115	+14	+7	+5.1	+2.6
11	32	30	104	67	4.33	2.79	.0125	.0115	+9	0	+3.4	+0.1
12	34	32	129	79	5.42	3.29	.0137	.0116	+12	+1	+4.1	+0.2
13	33	32	116	103	4.83	4.29	.0149	.0121	+12	+5	+4.4	+1.9
14	24	25	5	9	0.20	0.38	.0143	.0123	−6	+2	−2.2	+0.8
15	27	27	65	52	2.71	2.17	.0125	.0117	8	−6	−6.5	−2.0

[1] Following is an explanation of the data in the several columns of the table.

Daily mean temperatures are from the daily extreme

$$\frac{\text{Max.}+\text{min.}}{2}$$

Hour degrees.—The summation of the excess of the hourly temperatures above 32° represents the hour degrees for that day. As a rule the excess of the afternoon temperatures coincide with the hour degrees for any day.

Day degrees.—A day degree is considered as an average excess of a whole degree above 32° for the 24 hours.

If the temperature of each hour of the 24 were 33°, there would be an excess of 24°, which, divided by 24, equals 1 day degree. Since, however, in nature, the excess in temperature above 32° is not uniformly distributed throughout the 24 hours, but is generally grouped around the afternoon hours, the problem becomes one of seeking a working unit of temperature that will be significant in snow melting. The figures in the column "day degrees" represent, the excess of daylight temperatures above 32 divided by 24. The hourly record by thermograph provides the means of arriving at the figures. It should be remembered that the temperature of the south slopes is almost always a few degrees higher on the average than those of the north slopes. Only north-slope temperatures appear in the table.

The run-off is given in depth over the watershed; the 24-hour changes are given in "depth over watershed" and also in "cubic feet per acre," the latter for comparative purposes, since to express the small fluctuations of winter in the unit "depth over watershed" would necessitate the use of an undesirable number of decimal places.

Some time has been devoted to seeking a convenient working index to the temperature at which snow melting and surface run-off begin. For tentative purposes, it may be said that an excess of a single day degree will start slight surface run-off. A weekly mean maximum temperature of 35° is also effective to about the same degree. Considerable run-off is indicated whenever the weekly mean maximum approaches 40° or the excess in day degrees amounts to 4 or more. The amount of run-off for the same temperature varies, however, with the season and the nature of the snow, whether old or fresh, and probably other conditions, especially the *duration* of the high temperature. Both streams are sensitive to changes in temperature, A being more so than B, as may easily be seen by an examination of the tabulations herein presented. Whenever the run-off is increasing on both streams, as a result of relatively high temperature, a fall in temperature of a few degrees immediately checks the run-off on A, but in a considerably less degree on B, the full effect on B appearing a day or so later, as may be seen from the few examples selected and presented in Table 32. A sudden fall in temperature almost invariably causes the discharge of A to diminish, but it may scarcely affect B.

TABLE 32.—*Effect of sharp fall in temperature on discharge of both watersheds.*

Date.	A. Change in—		B.		Snowfall (inches).
	Daily mean temperature (degrees).	Daily discharge (cubic feet per acre).	Daily mean temperature (degrees).	Daily discharge (cubic feet per acre).	
1913.					
Jan. 5	−15.2	+0.2	−24.7	−0.1	5.3
6	− 6.8	− .3	− 6.9	0	....
7	+ 4.0	− .8	+ 3.1	− .1	....
8	+11.0	− .1	+ 9.6	− .4	....
	....	−1.0	....	− .6	....
1916.					
Jan. 12	−16.7	− .3	−17.4	− .4	....
13	+ 8.7	− .3	+ 7.2	− .1	....
14	+ 9.4	− .1	+10.6	0	....
	....	− .7	....	− .5	....
1917.					
Jan. 21	−15.2	+ .5	−15.4	0	10.4
22	−11.5	− .6	−12.4	0	....
23	+ 4.1	0	+ 4.3	− .3	....
24	+ 4.8	− .5	+ 4.8	− .4	0.2
25	+ 9.2	− .2	+ 7.5	− .2	....
	....	− .8	....	− .9	....
1918.					
Jan. 19	−16.9	− .3	−17.3	0	1.3
20	− 4.3	− .5	− 4.1	0	0.4
21	− 4.3	−1.3	− 4.5	− .6	....
22	− 6.6	− .9	+ 5.0	− .7	....
23	+10.5	− .3	+12.0	0	....
	....	−3.3	....	−1.3	....

Still referring to Table 31, it is to be observed that as a result of the slight increase in the temperature beginning on the 6th and ending on the 11th there was a slightly increased stream flow susceptible of definite measurement, more particularly on A, beginning about the 15th. It is reasonable to refer this small increase in streamflow to the excess in day degrees of temperature, beginning as above on the 6th. It is also to be noted that the excess of day degrees of temperature in both the second and third decades of February was less than in the first decade and that in general the run-off decreased after the 19th (Table 33). The increase in run-off during February that can perhaps be ascribed to run-off from melted snow was 0.0091 inch on A and 0.0044 inch on B.

TABLE 33.—*Decade temperature and stream flow, February and March, 1916.*

	Mean daily temperature.		Total excess day (degrees).		Total run-off (inches over watershed).		Run-off computed (inches over watershed).		Difference.	
	A	B	A	B	A	B	A	B	A	B
Feb. 1-10	18.3	17.7	5.95	4.91	0.0680	0.0847	0.0680	0.0840	0	−0.0007
11-20	21.3	20.1	3.66	2.41	.0733	.0854	.0680	.0840	−0.0053	− .0015
21-29	21.9	21.9	2.46	2.04	.0650	.0778	.0612	.0756	− .0038	− .0022
Sum	.....	.....	.....	.....	.2063	.2479	.1972	.2436	− .0091	− .0044
Mar. 1-10	27.7	27.3	6.62	6.56	.0790	.0933	....	....	....	....
11-20	32.1	31.5	43.07	37.71	.1386	.1228	....	....	....	....

On February 1 watershed A was discharging at the rate of 0.0068 inch per day. Assuming that there was no increase in underground water, nor any contribution from surface flow, the total discharge for the 10 days would be 0.0680 inch. The actual discharge was 0.0680 inch. Considering the remaining decades in like manner Table 33 has been formed.

It will now be of interest to examine the records of snow depth for the months covered by Table 33. These data will be found in Table 34, from which it may be seen that on January 31 the average depth of snow, north slope stations was 36.6 inches. The average depth at the four south slope stations was 24.6 inches. Table 34 further shows that for the 10 days ending February 10, the average depth on north slope watershed A had decreased 5.0 inches; adding the snow which fell during that period, 0.6 inch, the total decrease is seen to have been 5.6 inches.

The average depth on February 20 was, north slope 28.3 inches, south slope 13.8 inches. There was no snow of consequence during the second decade.

TABLE 34.—*Depth of snow on watershed A (in inches).*

Station.	January, 1916.	February, 1916.			March, 1916.			
	31	10	20	29	5	10	15	20
South slope 2	28.8	22.8	19.4	20.8	22.8	17.4	9.0	T.
5	32.4	26.4	19.8	19.2	18.0	12.0	1.2	0.0
12	24.0	20.4	13.2	14.4	14.4	8.4	0.0	0.0
18	13.2	9.6	3.0	T.	2.4	T.	0.0	0.0
Mean	24.6	19.8	13.8	13.6	....	....	....	....
North slope 1	36.0	31.2	29.0	30.0	33.0	30.6	30.0	27.6
3	34.8	31.2	28.8	31.8	33.6	28.8	25.8	22.8
4	33.0	26.5	24.0	27.6	31.2	24.0	24.6	21.6
6	42.0	34.8	30.0	36.0	39.6	30.0	28.8	20.4
7	39.0	34.8	32.4	34.8	38.4	32.4	32.4	29.4
8	36.0	31.2	28.2	30.0	32.4	27.6	24.0	19.2
9	38.4	33.6	31.8	33.6	38.4	33.6	30.6	26.4
10	47.4	40.8	39.6	42.0	46.8	42.0	40.8	38.4
11	38.4	34.2	32.4	36.0	39.6	33.6	32.4	28.2
13	46.8	42.6	39.6	42.0	46.2	42.0	39.0	36.0
14	43.2	37.8	34.8	38.4	42.0	38.4	36.0	33.6
15	36.6	32.4	31.2	34.8	36.0	32.4	31.8	27.6
16	37.2	33.6	28.8	30.0	33.0	27.6	22.8	14.4
17	44.4	39.4	36.0	38.4	42.0	37.2	34.8	32.4
D	43.2	36.6	35.4	39.6	42.6	39.6	32.4	34.8
Mean	36.6	31.6	28.3	30.5	33.3	28.3	25.1	21.7

The average depth on February 29 was, north slope 30.5 inches, south slope 13.6 inches. The total snowfall for the nine days was 3.8 inches, hence the diminution in depth, north slopes, was actually 1.6 inches. Considering the month as a whole, the south slopes, excepting No. 18 only, still carried a snow cover. Practically all of the 13.2 inches of snow on No. 18 at the beginning of the month, plus that which had fallen in the meantime, had disappeared by the 29th.

The water equivalent of the 13.2 inches of snow on January 31 was 2.90 inches; since snow-scale No. 18 forms but 13 per cent of the watershed, that amount would correspond to 0.377 inch over watershed. The normal run-off for that amount of precipitation is 0.105 inch. If to that amount is added 0.160 inch as the probable evaporation for the month, as computation shows it would have been, the water equivalent obtained for the total disappearance of snow is 0.265 inch, whereas the measured run-off was only 0.207 inch.

In this computation no account has been taken of the shrinkage of the snow cover on the three remaining south slopes, nor any of the north slopes; only that amount of snow which has actually disappeared, either into the air or earth has been considered. It is obvious that there is some difficulty in accounting for the apparent loss of snow from the south slopes unless it be considered as being lost in part by evaporation and in part serving to replenish ground storage.

Still considering the data of Tables 32 and 33, it is further remarked that after the slight warming up in the first decade of February there is a small increase in the run-off, greatest in the second decade and falling off somewhat in the third decade. It seems reasonable to ascribe this increase in run-off directly to the small rise in temperature before referred to in connection with the disappearance of the snow cover on snow-scale area No. 18.

The detailed data for the first and second decades of March, Table 33, are also interesting in showing the prompt response of the streams to temperatures at which run-off begins.

During the first decade of March the temperature was rather uniformly low until the 7th. From the 7th to the 10th the average daily excess above 32° was 7.8 day degrees, and melting attended by surface run-off was active on both watersheds. The cumulative effect of these three days of relatively high temperature is seen in the run-off of the second decade of the month in which, for the first time during the low-water season, the discharge of A exceeds that of B for a 10-day period.

Still another table (Table 35) is presented illustrating the relations between temperature and run-off. In this table actual daily mean temperatures and the changes from day to day are given, and these may be compared with the increase or decrease in the daily discharge on an acre basis. The period covered by this table includes the greatest run-off from melting snow that has as yet occurred in the experiment. From the figures of this table it appears that whenever in April the daily mean temperature passes above freezing even for a single day, there is a decided increase in the discharge. When it remains over 32° for several days the volume of the discharge increases, but only so long as the mean temperature continues to increase. For example, if the mean temperature on the third day reaches 36° and on the fourth day falls back to 34°, the discharge of the fourth day, as compared with the third, diminishes. (See the dates of increasing volume of discharge due to air temperatures, as follows: April 12 to 14 and 21 to 26, inclusive; May 1 to 3 and 11 to 20, 1917.

The dependence of the ratio B/A upon the temperature is also excellently illustrated in Table 35 (see the column on the extreme right).

TABLE 35.—*Temperature and run-off relations, flood 1917.*

Date.	Mean temperature.		Daily change.		Discharge.		Daily change.		Ratio, B/A.
	A	B	A	B	A	B	A	B	
1917.					*Cu. ft. per acre.*	*Cu. ft. per acre.*			
Apr. 1..	12.2	12.4	−12.5	−12.0	31.1	37.8	− 4.3	− 1.8	122
2..	15.9	16.2	+ 3.7	+ 3.8	29.1	36.8	− 2.0	− 1.0	126
3..	15.3	16.4	− .6	+ .2	28.7	36.6	− .4	− .2	128
4..	20.1	19.2	+ 4.8	+ 2.8	28.2	36.0	− .5	− .6	128
5..	29.3	29.0	+ 9.2	+ 9.8	30.4	37.0	+ 2.2	+ 1.0	122
6..	26.3	27.2	− 3.0	− 1.8	31.8	37.4	+ 1.4	+ .4	118
7..	28.4	28.2	+ 2.1	+ 1.0	32.8	38.4	+ 1.0	+ 1.0	117
8..	35.4	34.1	+ 7.0	+ 5.9	37.3	40.7	+ 4.5	+ 2.3	109
9..	31.5	31.6	− 3.9	− 2.5	42.4	43.5	+ 5.1	+ 2.8	103
10..	28.0	27.8	− 3.5	− 3.8	38.9	44.6	− 3.5	+ 1.1	115
11..	29.2	28.0	+ 1.2	+ .2	39.8	43.8	+ .9	− .8	110
12..	34.1	34.0	+ 4.9	+ 6.0	46.4	44.6	+ 6.6	+ .8	96
13..	34.7	35.0	+ .6	+ 1.0	52.3	46.4	+ 5.9	+ 1.8	89
14..	35.2	35.5	+ .5	+ .5	62.1	48.6	+ 9.8	+ 2.2	78
15..	30.0	31.0	− 5.2	− 4.5	66.2	48.8	+ 4.1	+ .2	74
16..	26.9	26.9	− 3.1	− 4.1	60.8	48.2	− 5.4	− .6	79
17..	30.2	29.8	+ 3.3	+ 2.9	54.8	47.4	− 6.0	− .8	86
18..	29.0	28.0	− 1.2	− 1.8	49.3	45.5	− 5.5	− 1.9	92
19..	21.8	22.5	− 7.2	− 5.5	45.8	44.7	− 3.5	− .8	98
20..	25.5	23.8	+ 3.7	+ 1.3	44.6	45.4	− 1.2	+ .7	102
21..	33.0	31.5	+ 7.5	+ 7.7	50.7	50.5	+ 6.1	+ 5.1	100
22..	37.1	35.8	+ 4.1	+ 4.3	75.7	63.5	+ 25.0	+ 13.0	84
23..	36.9	37.2	− .2	+ 1.4	107.8	87.6	+ 32.1	+ 24.1	82
24..	38.2	38.9	+ 1.3	+ 1.7	155.6	114.6	+ 47.8	+ 27.0	74
25..	40.6	40.5	+ 2.4	+ 1.6	207.4	141.8	+ 51.8	+ 27.2	69
26..	41.2	41.9	+ .6	+ 1.4	230.3	172.0	+ 22.9	+ 30.2	75
27..	30.3	30.3	−10.9	−11.7	192.0	174.3	− 38.3	+ 2.3	91
28..	28.2	28.8	− 2.1	− 1.4	134.9	165.3	− 57.1	− 9.0	122
29..	26.8	25.9	− 1.4	− 2.9	110.4	152.8	− 24.5	− 12.5	139
30..	27.2	27.0	+ .4	+ 1.1	100.7	136.0	− 9.7	− 16.8	135
May 1..	36.1	36.6	+ 8.9	+ 9.6	106.1	135.6	+ 5.4	− .4	129
2..	35.5	35.0	− 0.6	− 1.6	117.1	156.7	+ 11.0	+ 21.1	135
3..	33.2	33.6	− 2.3	− 1.4	137.5	177.0	+ 20.4	+ 20.3	127
4..	30.5	30.9	− 2.7	− 2.7	191.3	186.1	+ 53.8	+ 9.1	98
5..	22.8	23.5	− 7.7	− 7.4	170.0	191.7	− 21.3	+ 5.6	113
6..	24.2	24.5	+ 1.4	+ 1.0	147.6	183.2	− 22.4	− 8.5	124
7..	27.7	27.6	+ 3.5	+ 3.1	126.2	171.1	− 21.4	− 12.1	136
8..	26.2	26.6	− 1.5	− 1.0	115.3	157.2	− 10.9	− 13.9	137
9..	28.3	28.4	+ 2.1	+ 1.8	110.7	148.6	− 4.6	− 8.6	135
10..	32.2	31.6	+ 3.9	+ 3.2	111.4	143.6	+ .7	− 5.0	129
11..	33.3	32.6	+ 1.1	+ 1.0	112.7	148.1	+ 1.3	+ 4.5	131
12..	34.2	34.0	+ .9	+ 1.4	126.3	157.7	+ 13.6	+ 9.6	126
13..	41.4	41.1	+ 7.2	+ 7.1	166.1	181.6	+ 39.8	+ 23.9	110
14..	45.6	45.2	+ 4.2	+ 4.1	326.0	225.9	+159.9	+ 44.3	69
15..	40.8	40.0	− 4.8	− 5.2	660.2	292.1	+334.2	+ 66.2	44
16..	41.8	41.0	+ 1.0	+ 1.0	765.2	419.0	+105.0	+126.9	55
17..	43.1	42.4	+ 1.3	+ 1.4	839.6	519.0	+ 74.4	+100.0	62
18..	42.7	41.7	− .4	− .7	857.8	588.5	+ 18.2	+ 69.5	69
19..	35.5	35.1	− 7.2	− 6.6	665.0	576.9	−192.8	− 11.6	87
20..	34.5	34.6	− 1.0	− .5	513.1	506.8	−151.9	− 70.1	99

Diurnal variation in streamflow.—The diurnal variation in the flow of the two streams has been computed for the eight years, July, 1911, to June, 1919, and the results have been plotted in figure 21. These curves are both instructive and illuminating—illuminating in that they show more clearly than would otherwise be possible the response of the streams to the meteorological conditions as modified by the physical characteristics of the two watersheds. The several monthly variations have been combined in a seasonal mean, each of which is based on approximately 20,000 observations.

The curve for winter (December, January, and February) is one of very small amplitude, but a weak response to the warm hours of the afternoon can be seen more pronounced on B than on A and the maximum seems to occur at 2 p. m. while on A it is deferred until 5 p. m.

The curve for spring (March, April, and May) is a composite made up of March and April, both of which show a weaker response to the increased insolation than May, the flood month. The dominant feature of the spring or flood curve, since all of the floods except the October rain floods are comprised within it, is the very wide variation of A as compared with B and the fact that the crest of the maximum daily discharge of the afternoon is reached

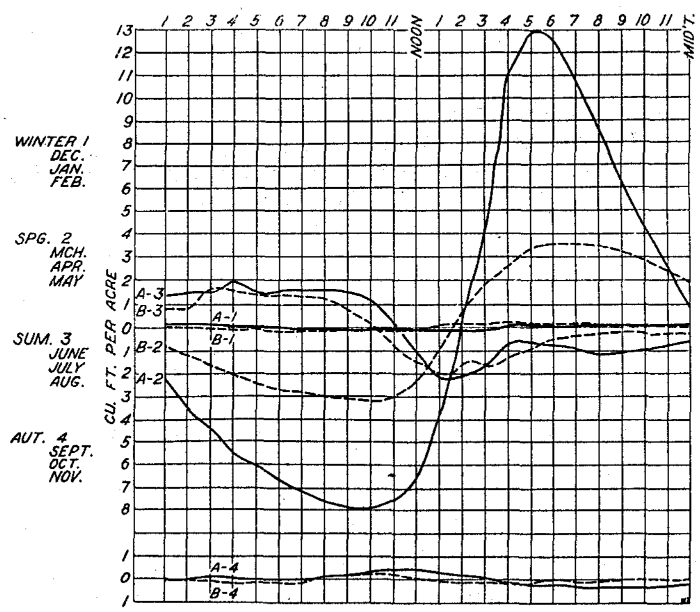

FIG. 21. Average diurnal streamflow, A and B.

at 3 p. m. and is sharply defined, whereas the crest of the maximum daily discharge on B is not sharply defined and is reached at 6 p. m. instead of 3 p. m. Doubtless this is due to a greater time being required for concentration of run-off on B than on A, as elsewhere stated.

The summer curves, June, July, and August, for the two streams are similar in most respects but dissimilar to the curves for any of the other seasons in the fact that the greatest variation above the mean is found between midnight and 9 or 10 a. m.; thereafter there is a very decided decrease up to midnight. The maximum posipositive departure for the 24 hours in June occurs from midnight to 1 a. m. and is due to the fact that during June the streams are declining and the decline in the absence of precipitation is in direct proportion to the elapsed time. Accordingly the stage on June 1 at midnight is generally the highest of the month, and it continues to recede during the remainder of the month.

Another interesting fact which comes out on inspection of the summer curves is the decided dip in the curve beginning about 9 a. m. and reaching a minimum on B at 1 p. m. and on A at the same hour. This dip in the curve represents the daily loss due to transpiration and evaporation, and the loss seems to be greater on B than on A for a part of the day at least.

The autumn curves are quite similar to the winter curves, the amplitude of the variations being quite small, as might be expected. A exhibits, however, a wider variation than B, much as it does during the spring melting period.

STREAMFLOW DATA AND RELATIONS FOR EIGHT YEARS.

In the following pages there are presented all of the streamflow data in statistical form for the eight years from October, 1911, to September, 1919. It has already been explained that prior to about August 1, 1911, the streamflow measurements were too inaccurate to be depended upon. The denudation of watershed B began about July 1, 1919. Hence it may be assumed that during the months of July, August, and September the streamflow from that watershed, on minutest inspection, would be found to be somewhat affected. For this reason the data for these three months will not be presented, except in the summary of relations for whole years, being necessary to complete the year, which begins October 1, 1918. On examination it will be seen that the insertion of this last year has practically no effect on the mean values for precipitation or run-off, the year being in itself more nearly "normal" than any other.

Owing to the fact that diagrams lettered A to L, inclusive, are based upon but eight years' observations—all that are available—it is understood that there may be some uncertainty in the results drawn from those portions of the said diagrams that are confessedly based on insufficient data. In case the limits of the data of rainfall and run-off for watershed A do not fall within the limits of the diagrams or fall upon a portion of the said diagrams that is based on insufficient data, the most probable value sought will of course have to be determined in such other way as may appear most logical.

After considering the yearly averages, the various seasons are discussed in the order mentioned at the beginning of this chapter.

In all of the following calculations, where it has seemed desirable to transpose the original rates of stream discharge into cubic feet per acre or inches over either watershed, the following transposition factors have been used:

	A	B
1 C. F. S. equals cubic feet per acre-day	388. 3	431. 1
1 C. F. per acre equals inches over watershed	1/3, 630	1/3,630
1 C. F. S. equals inches over watershed per day	0. 1070	0. 1188

Relations of the streams for whole years.—The precipitation and run-off data for the eight years ending September 30, 1919, are given in Table 36, together with calculations showing the relation of total run-off of each watershed to precipitation.

On the mean amounts of precipitation for the two watersheds for eight years are almost the same, but in individual years they show considerable variation. This raises the question as to whether one watershed may actually receive more precipitation than the other, or whether the differences noted are due solely or largely to peculiarities of gage-catch. No doubt in some summer rains, which in mountainous regions are often very local in character, one watershed may receive more precipitation than the other, and for the whole year 1912–13 it is evidenced by both the precipitation and streamflow records that watershed B must have received appreciably more than watershed A. In the case of winter snowfall, however, since the storms often last for many hours, there is practically no opportunity for differences in the actual fall of the two areas. Yet the winter months show fully as great variations in catch as do the summer months. The conclusion is obvious that differences between the two areas in matters of precipitation are more apparent than real.

In view of these facts, it seems more desirable, as well as simpler, to base all comparisons of streamflow and precipitation on the precipitation of A watershed alone. It might be argued that the average of the two would be even better. The answer is that while discrepancies between the two have, in the past, pretty well evened up over a long period, still there is no assurance, now that watershed B is denuded, that a catch can be obtained, with the greater exposure of gages to the wind, at all comparable to that obtained on A.

The use of the single record can not be seriously objected to when it is considered that at the lower end of watershed A there is the choice of the better catch of two gages, and this value is averaged with the catch of a third gage at the head of the watershed.

TABLE 36.—*Precipitation and run-off for years beginning Oct. 1.*

Year.	Precipitation (inches over watershed).			Run-off (inches over watershed).				Proportion of precipitation appearing as run-off.		$B/A - R/Pa$.
	For the year.		Difference $B-A$.	For the year.		Difference $B-A$.	Ratio B/A.	R/Pa.		
	A.	B.		A.	B.			A.	B.	
1911–12.....	21.30	21.49	+0.19	8.368	8.367	−0.001	1.000	0.393	0.393	0.607
1912–13.....	18.63	19.66	+1.03	4.778	5.213	+ .435	1.091	.256	.280	.834
1913–14.....	22.64	21.84	− .80	5.629	5.551	− .078	.986	.249	.245	.737
1914–15.....	19.97	19.85	− .12	5.354	5.405	+ .051	1.011	.268	.271	.743
1915–16.....	22.71	23.13	+ .42	5.596	5.553	− .043	.992	.246	.245	.746
1916–17.....	22.88	22.78	− .10	9.644	9.839	+ .195	1.020	.422	.430	.598
1917–18.....	18.90	18.85	− .05	3.196	3.531	+ .335	1.105	.169	.187	.936
1918–19.....	21.13	21.15	+ .02	6.081	5.968	− .113	.981	.288	.282	.693
Means.	21.02	21.09	+ .07	6.081	6.178	+ .098	1.023	.2864	.2916	....
Sums..	168.16	168.75	+ .59	48.646	49.427	+ .781	8.186	2.291	2.333	....

The following points with reference to the data of Table 36 are noteworthy:

1. The precipitation is unusually uniform from year to year.

2. The amount of water discharged by stream A varies greatly from year to year, and may be from 17 to 42 per cent of the precipitation.

3. The amount of water discharged by stream B is, on the whole, about 2 per cent greater than that for stream A. This immediately suggests that evaporation must be the less on B, either by reason of the cover conditions or because B has a deeper and better storage reservoir, or both.

4. On closer examination (see diagram A) it is seen that the ratio of B to A total discharge is highest in the years when, either because of relatively low precipitation or other causes, the total streamflow is least. In the case of the year 1912–13 it is probable that the very high ratio B/A is due in part to an actual excess of precipitation on B, and some allowance should be made for this.

The relation of the two streams approaches unity only in years whose precipitation and evaporation tendencies are about normal. On the other hand, B streamflow again tends to become greater than that of A when the total amount discharged by either is unusually great. The two years exhibiting this are 1911–12 and 1916–17. In the former there was a heavy spring flood, as well as a very considerable discharge from October rains. In the second case the flood was unusually large, comprising over 70 per cent of the total run-off for the year.

In such cases it is evident the storage facilities of both watersheds may be filled to capacity, and watershed B, being able to deliver a larger amount of water for streamflow in a given time, naturally makes the better showing.

Although these relations of the two streams do not express themselves as a simple curve, they are so simple that the acceptability of the relations as shown by diagram A can hardly be questioned. On the other hand, the true curve for the data represented by diagram A is almost impossible to draw. It has, therefore, been sought to express the causes of variation in the ratio B/A, as described above, by introducing another element. The two years of greatest stream discharge were also the two years in which the ratios of discharge to precipitation were highest, while the other extreme of the diagram represents a year in which the relative amount of streamflow was excessively low. It is, therefore, suggested that the amount of run-off relative to precipitation has a direct bearing on the relation of the two streams for whole years. Whenever the streamflow is *relatively* high (or the evaporation a relatively small percentage of the whole disposal), then the ratio of B to A discharge will be heightened.

In the last column of Table 36 the data for diagram AA have been worked out. The abscissæ are obtained by deducting from the ratio B/A the ratio, in corresponding terms, between the run-off and precipitation of watershed A. The ordinates are, as in diagram A, the run-off in inches of watershed A. The curve might be made straighter, and the relations more fully expressed, by making an even greater allowance for large or small

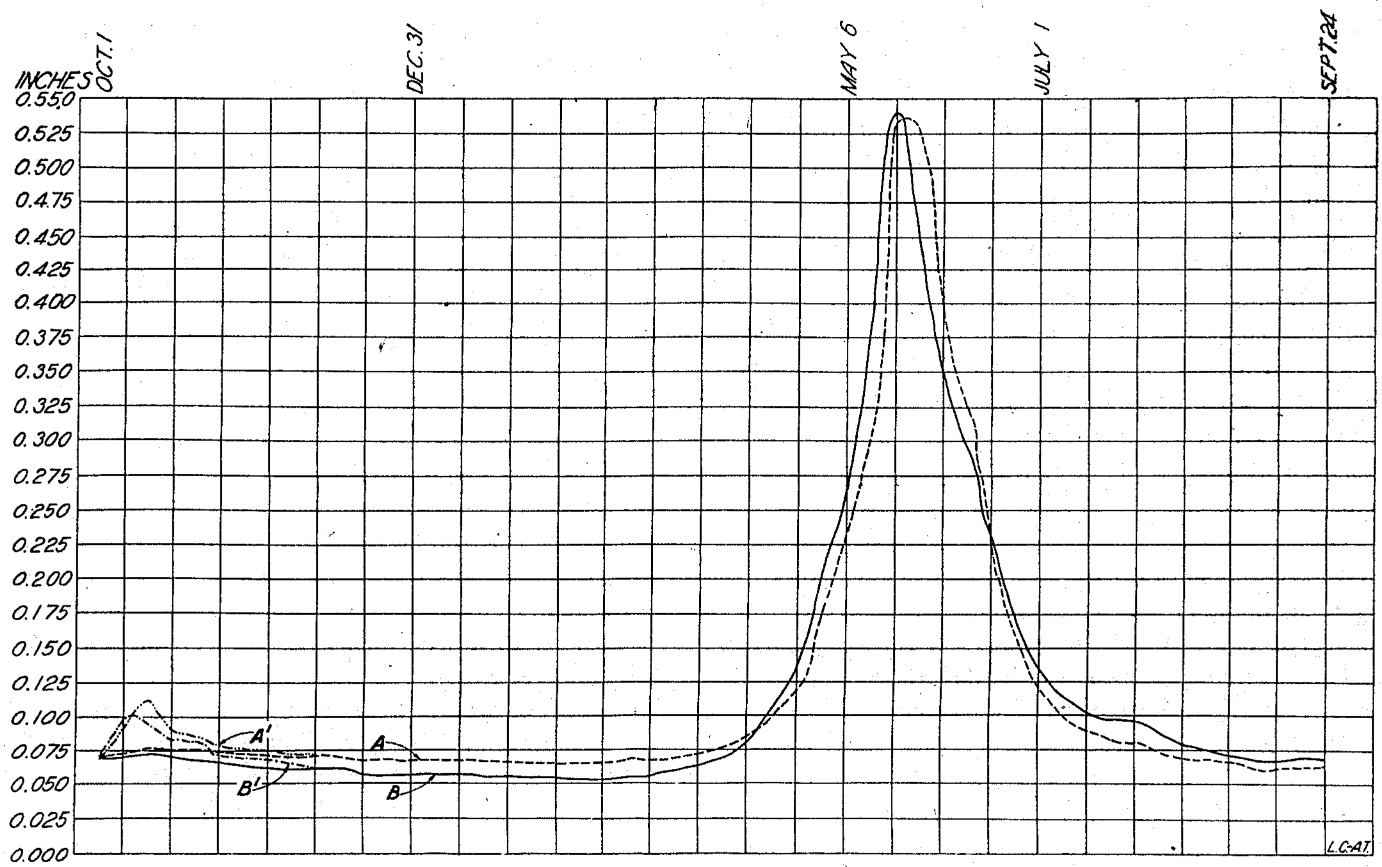

FIG. 22. Average weekly streamflow, A and B. The curves A' and B' result from including the flow of October, 1911.

ratio P/R (say one and one-half times), but the use of the straight term P/R brings the data within the range of easy handling.

The relations may be summarized for reference in the future, as follows:

RULE 1. *Between the extremes of 18 and 23 inches of precipitation, and of 3 and 10 inches of discharge from Watershed A, it is recognized that the ratio of annual discharges, B/A, should never be greater than 1.11 nor less than 0.98, with a mean value of 1.02. The ratio is slightly less than 1.00 only when there is about a normal balance between streamflow and precipitation, represented by 5 or 6 inches for the former and 20 to 22 inches for the latter, and increases either when precipitation and run-off are low, or run-off is very great, due to large volumes in flood. To compute the most probable flow of B, relative to A, for conditions existing prior to denudation, or any year beginning October 1 and ending September 30, the total flow of A will be taken as the guiding condition, in accordance with diagram AA. To the ratio indicated on diagram AA, for a given discharge of A in inches over watershed, will be added an amount, expressed in similar terms, representing the ratio of A run-off to A precipitation for the year. The sum will be the probable ratio of B discharge to A discharge, when both are expressed in inches over the watershed. (For example, if A discharge is 7 inches, and the annual precipitation 20 inches, the indicated ratio is 0.641, and to this must be added seven-twentieths or 0.350, which gives the ratio B/A of 0.991.) The probable error in this method is less than 0.5 per cent of the final result.*

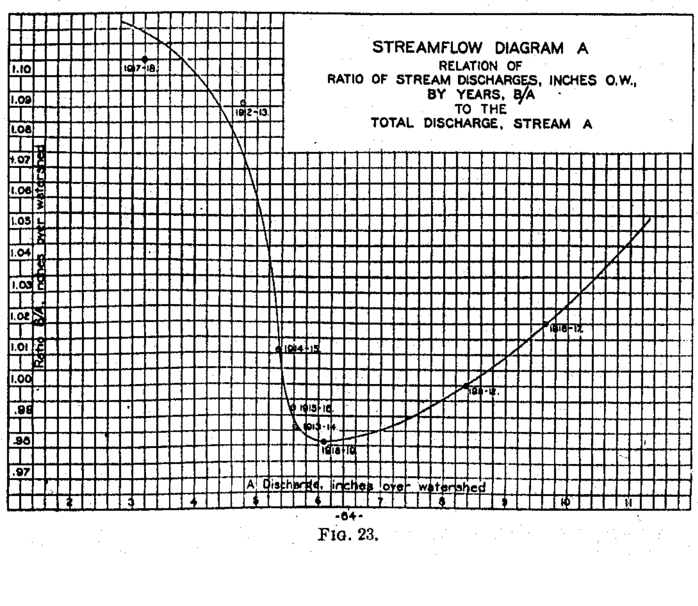

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FIG. 23.

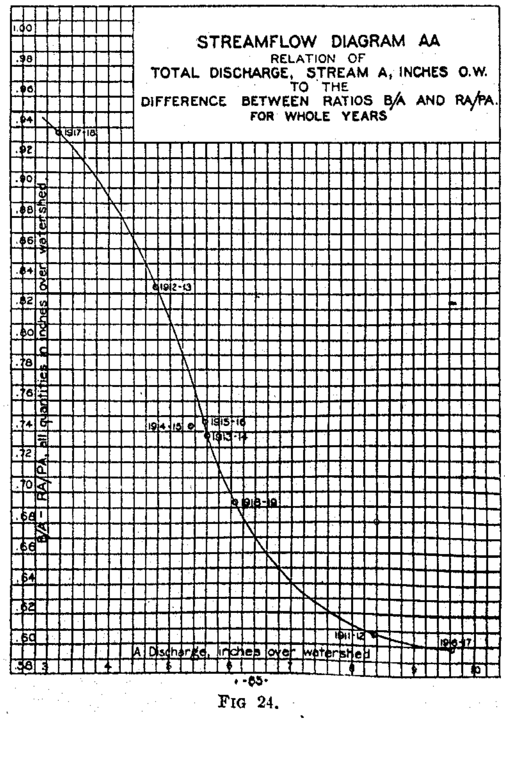

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FIG 24.

Relations of the streams in the spring flood.—As is shown by figure 22, which gives the average stream discharges by 14-day periods for 1911 to 1917, the rise of the spring flood usually begins in the latter part of March, and the heaviest discharge is usually recorded in the second decade of May. There is a tendency, in spite of variable weather and different amounts of snow, for the culmination of influences to be reached about that time.

In spite of the fact that successive floods show similar characteristics, especially in the general shapes of the A and B curves, it has been found impossible to establish any fixed relations between the rates of discharge of the two streams at intermediate stages in the flood. While, as has been stated, stream B lags behind stream A during any rise, the flood as a whole is made up of so many rises and recessions that this relationship usually becomes very complicated before the crest on either stream is reached.

Beginning of the flood.—In Table 37 are presented the data bearing upon the relations of the two streams at the beginning of the spring flood. The initial date of the flood is taken to be the first day on which the discharge rate of stream A exceeds 0.100 C. F. S. Not infrequently, after a melting period which will produce such a discharge, there occurs colder weather in which the rate for stream A may again fall to 0.100 C. F. S. or less. As neither stream, during the period up to the final rise, is making any net gain, it naturally follows that the relationships during such periods are not those based on the inherent lag of stream B. The latter may have opportunity to overtake stream A before the final and more rapid rise begins. Consequently, it is thought best to consider this period of uncertain or slow melting as a separate stage, even though the volumes of water involved may be very small in comparison with the whole flood volumes.

TABLE 37.—*Conditions at beginning of flood.*

Year.	Initial date.	Discharges on initial date.				
		C. F. S.		Inches O. W.		
		A	B	A	B	Ratio.
1912	Mar. 6	0.102	0.091	0.0109	0.0108	0.991
1913	Apr. 29	.105	.094	.0113	.0111	.983
1914	Apr. 5	.109	.113	.0116	.0135	1.155
1915	Apr. 12	.101	.098	.0108	.0117	1.082
1916	Mar. 10	.108	.096	.0116	.0115	.989
1917	Mar. 29	.119	.092	.0127	.0109	.860
1918	Apr. 23	.108	.092	.0115	.0110	.958
1919	Apr. 4	.107	.094	.0114	.0112	.978
Averages	Mar. 30	.1075	.0962	.01148	.01146	1.000

Year.	Initial date.	Period of uncertain melting.				Discharge on and after highest day.		
		Final date.	Total volume.			Amount.	Number of days.	Amount corrected[1] for number of days.
			A	B	Ratio.			
1912	Mar. 6	Apr. 2	0.2822	0.3082	1.092	0.0852	8	0.0212
1913	Mar. 29	....	....	....	....	....	......	....
1914	Apr. 5	....	....	....	....	....	......	....
1915	Apr. 12	Apr. 17	.0332	.0748	1.183	.0425	4	.0105
1916	Mar. 10	Apr. 7	.3753	.3878	1.033	.2248	18	.0808
1917	Mar. 29	Apr. 8	.1021	.1155	1.131	.1021	11	.0141
1918	Apr. 23	....	....	....	....	....	......	....
1919	Apr. 4	Apr. 11	.0841	.0911	1.082	.0727	7	.0167
Averages	Mar. 30	....	....	....	1.1044	....	......	....

[1] Reduce amount 0.008 for each day, including and following highest day of period.

Table 37 indicates, only the initial rises due to snow melting being considered, that there is only slight variation in the ratios B/A for the initial day, and that on the average the relation of the two streams is expressed by unity. On plotting the ratios, however, in relation to the height attained by stream A on this initial day, it is found that there is a fairly consistent relationship. It is probable that the relationship is controlled by the *rate of rise* rather than the head attained by stream A, but we have been unable to find a key which exactly fits the situation.

It is also to be noted that in every listed period following the initial dates, when the streams fell back, the discharge of B exceeded that of A by an amount not varying greatly from 10 per cent. It is practically certain that the relations during such a period depend largely on the opportunity given for stream B to overtake and exceed stream A in delivery. The longer the period after A has reached the highest point, the greater should be the ratio B/A. But this ratio will tend to be lowered, other things being equal, if stream A has reached a relatively high point and discharges a relatively large volume thereafter. The most consistent relationship is found, then, by plotting the ratios B/A for the whole period against the volume discharge of A, with a minus correction for each day elapsed from the highest day to the end of this period of uncertain or suspended melting.

The relations at the beginning of the flood period may be formulated as follows:

RULE 2. *The ratio of B discharge in inches over watershed to the similar discharge for A on the first day of the spring rise in which stream A shows a rate of more than 0.100 C. F. S. is on the average 1.00, but may vary in different years by plus or minus 15 per cent. To determine the suppositional ratio after denudation, reference will be made to the discharge of stream A in C. F. S., and the corresponding value will be read from diagram B.*

RULE 2A. *In the event that the discharge rate of stream A, after the initial date of the flood, should again fall to or below 0.100 C. F. S., the ordinary relationship of the two streams in the early rise, with A leading B, may be reversed, so that on the average B will discharge about 10 per cent more for the whole of such a period. To determine the suppositional ratio B/A for such a period, from the initial day to the day next preceding the final rise above 0.100 C. F. S. (both dates included) in inches over watersheds, reference will be made to the discharge of stream A for that portion of the period beginning with the day of greatest discharge. The computed flow of A in inches over watershed will be reduced 0.008 inch for each day of the period including and following the crest day. The value thus obtained will be referred to diagram BB, from which the ratio B/A for the whole period may be obtained.*

End of the flood.—The relations existing between the two streams at the end of the flood are important, not only in allocating the volume which has been discharged but also because this relation is reflected throughout the summer period.

The end of the flood is taken to be the last day on which stream A has a discharge of 0.150 C. F. S. or more. Should such a discharge occur after a dip below 0.150, it would be allocated to the summer period. One exception has been made in order to give some semblance of character to the very small flood of 1918. Here the crest day showed a rate of only 0.157 C. F. S. for A, the following day 0.148, and the third day 0.151. The last was taken as the closing day of the flood.

In general, the relation between the streams at the arbitrary date is seen to be controlled by the extent to which watershed B has had opportunity to exercise its

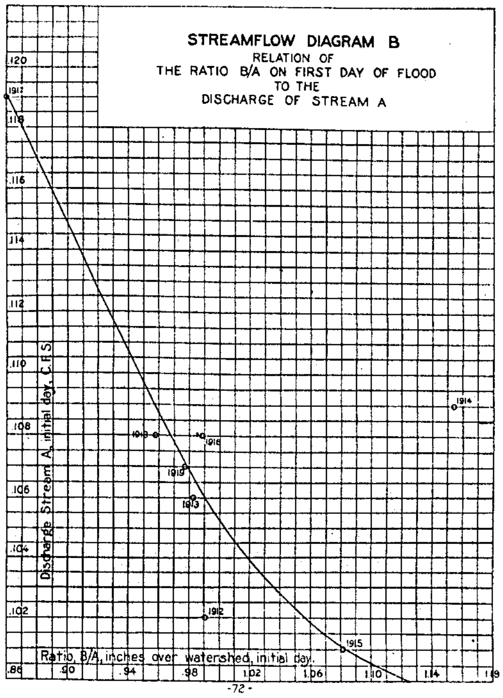

FIG. 25.

ability to drain out the surcharge of water from snow melting more rapidly than watershed A. The extent to which this has occurred and the extent of depression of the ratio B/A would, naturally, depend very largely on the length of the draining-out period. On trial, however,

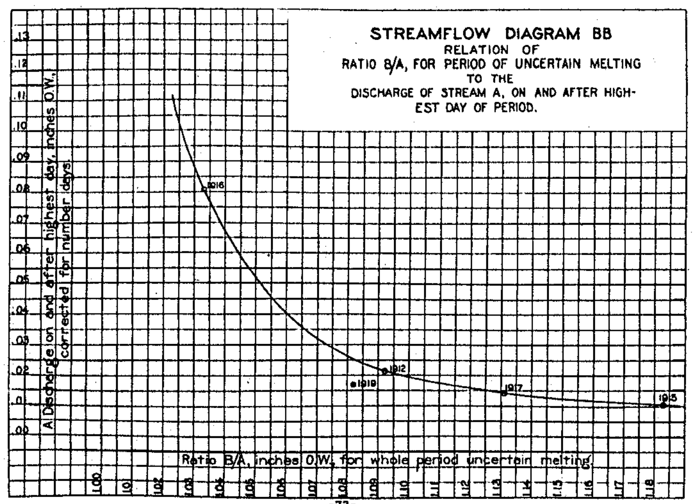

FIG. 26.

it is found better to express this period in volumes discharged rather than in days.

There are four conceivable and rather distinct sets of conditions which produce the relation at the end of the flood:

1. If the flood is exceptionally small, as in 1918, the end of the flood as determined by A discharge rate may occur before stream B has crested, in which event the relation would be a low ratio B/A due to the lag of B during any considerable rise.

2. If the end should occur while B is at or near its crest, the ratio might be higher than unity.

3. From this point on, greater flood volumes will tend to produce lower and lower ratios B/A at the end, by allowing B greater opportunity to drain out, providing only that the melting of snow is fairly continuous, and produces a sharply conical flood crest on stream A.

4. In the event of suspended melting at about the time when stream A has crested (as a result of daily and hourly temperature distribution as affecting snow melting on the two watersheds), there may be a secondary crest on A, a relatively large volume discharged after the primary crest, a much belated and high crest on B, and consequently a high ratio B/A maintained to the end of the flood. Naturally, this is more likely to occur in years when there is a large volume of snow to be melted, so that in extension of the remarks under the preceding paragraph there is still a possibility of an increasing ratio B/A with floods of large volume.

The preceding conditions become less confusing and less conflicting in their actual effects if, instead of considering the volume discharged by A as the measure of the opportunity for B to drain out and reach a low position, we consider rather the proportionate discharge of A before and after its crest. The greater the amount discharged by A before its crest the greater will be the accumulated lag of stream B, so that the latter may have a considerable rise to make before it can subside to a subordinate position. Therefore a more logical relation is found between the streams in different years if the opportunity for B's subsidence, as expressed by A volume after its crest, is compared with the opportunity for B's delay as expressed by the volume of A before crest.

In general, B holds its highest position at the end of the flood when the rise and fall of A are about symmetrical, being influenced neither by any great amount of belated melting nor by precipitation after the crest. This condition is expressed by approximately a unity ratio, $\frac{\text{A discharge after crest.}}{\text{A discharge before crest.}}$

The ratio B/A at end of flood then steadily decreases if greater opportunity is given for B to drain out, as shown by a *relatively* large A volume after crest. This decrease continues until the ratio of A volume after crest to that before crest is about 2:1. Beyond this point, as represented by the years 1917 and 1913, with their flattened flood-crests for stream A, the ratio B/A at end of flood must again rise. Such a flattened crest on A is certain to mean belated melting, which in effect eliminates the opportunity for B to overtake and drain out in advance of A.

In addition to the above-mentioned influences on the relative positions of the two streams at the end of the flood, the amount of precipitation occurring during the period of decline of both streams must have its effect. Precipitation, especially toward the end of the flood period, tends to increase the ration B/A. This is especially noticeable in the graph for the year 1913, when, but for continuous rains, the flood would have ended nearly a month sooner, and with a ratio B/A of about 1: 1, in spite of the heavy flow after A crest. It is also noticeable in 1912, when there was considerable rain near the end of the flood. That falling earlier is, apparently, united with the water from melting snow, and merely increases the volume of flow after the crest. That falling late probably reaches the streams directly and has an independent effect.

Various methods of correcting for this rain factor suggest themselves, and a number have been carefully gone into. The objection to any direct use of the precipitation record is that the influence of rain is so variable, according to continuity, dryness of the ground at the time, and other conditions. It seems best, therefore, to estimate the possible effect of rain on the final ratio B/A, by noting its effect first on the flow of A. The last one-third of the period of decline for stream A has been chosen as the period in which the influence of rain is most likely to be felt. It is not suggested that earlier rain has no influence, but whatever that influence is, it is likely to be obscured by the later conditions.

The rate of decline of stream A in this last-third period affords the best index of the effectiveness of rain. As a basis of comparison, the daily rate of decline for discharges from 0.150 to 0.400 C. F. S., in periods not influenced by rain has been computed. These rates are, of course, influenced by cloudiness, evaporation, etc., and vary a good deal from day to day. Using the mean curve, it is possible to figure up from the rate of 0.150 C. F. S. by adding the daily changes, and to show quite closely what the rate of discharge would have been 15, 20, or 25 days before the rate of 0.150 C. F. S. was reached, if uninfluenced by rain. Thus, in the last 20 days of a flood, the "normal" decline would be from a head of 0.268 to a head of 0.150 C. F. S., or a change of 0.118 C. F. S.

To such a figure as the last, varying according to the length of the period, may be compared the actual decline of any given year. As example, the decline in 1912, for the last 20 days, was 0.074 C. F. S., which, compared with a "normal" of 0.118 C. F. S., gives the ratio 0.626 as expressing the influence of precipitation on the discharge of A. The smaller this decimal, or the greater the effectiveness of the precipitation, the higher the ratio B/A at the end of the flood may be expected to be. It has been found by trial that the influence of precipitation on stream B is about one-seventh more than its influence on A, at this season.

TABLE 38.—*Conditions at end of flood and other conditions relating thereto.*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Year.	Last day 0.150 C. F. S. or more.	Discharges at end of flood.					Ratio A discharge after crest to that on and before crest.
		Last day, C. F. S.		Last 3 days, O. W.[1]			
		A	B	A	B	Ratio B/A	
						Inches.	
1912	July 19	0.156	0.125	0.0491	0.0443	0.903	1.033
1913	June 28	.157	.165	.0486	.0578	1.188	4.420
1914	July 5	.154	.114	.0502	.0406	.808	2.011
1915	July 4	.150	.112	.0480	.0402	.837	1.227
1916	June 22	.151	.116	.0492	.0417	.850	0.918
1917	Aug. 2	.152	.110	.0486	.0390	.804	2.504
1918	May 8	.151	.102	.0479	.0364	.761	0.158
1919	July 5	.150	.105	.0489	.0380	.777	2.061

		(9)	(10)	(11)	(12)	(13)	(14)	(15)
		Conditions relative to rate of fall of A, last third.						
Year.	Last day 0.150 C. F. S. or more.	Decrease in discharge rate, C. F. S.	Number of days.	Full rate decrease this period.	Ratio actual to full decrease.	Ratio plus 6.	Sum divided by 7.	Corrected ratio column.
1912	July 19	0.074	20	0.118	0.626	6.626	0.2466	0.855
1913	June 28	.016	24	.162	.099	6.099	.8713	1.035
1914	July 5	.064	18	.099	.647	6.647	.9496	.767
1915	July 4	.077	15	.076	1.013	7.013	1.0019	.839
1916	June 22	.073	14	.069	1.058	7.058	1.0083	.857
1917	Aug. 2	.101	25	.175	.577	6.577	.9396	.755
1919	July 5	.083	20	.118	.703	6.703	.9576	.744

[1] To avoid possible marked effects of rain on the last day, use the sum for three days, including one before and one after the final day.

RULE 3.—*To determine the suppositional ratio B/A for the last day of the spring flood, when stream A has a discharge rate of 0.150 C. F. S. or slightly more, first compute the volume discharged by stream A up to and including the crest day for A, and the volume after the crest day and including the last day, and express the latter volume as a function of the former. By reference to diagram C, the approximate ratio may then be determined. The ratio indicated by the graph must, however, be corrected according to the extent to which the decline of stream A, in the last third of its declining period, has been influenced by precipitation. From the rate of discharge a given number of days before the end, subtract the rate on the last day; divide this quantity by the normal amount of decline for the given number of days as indicated by the table below; to the quotient add 6 whole units, and divide the sum by 7. This quantity, usually a little less than unity, will be divided into the ratio indicated by the graph, to obtain the true ratio for the last day of the flood.*

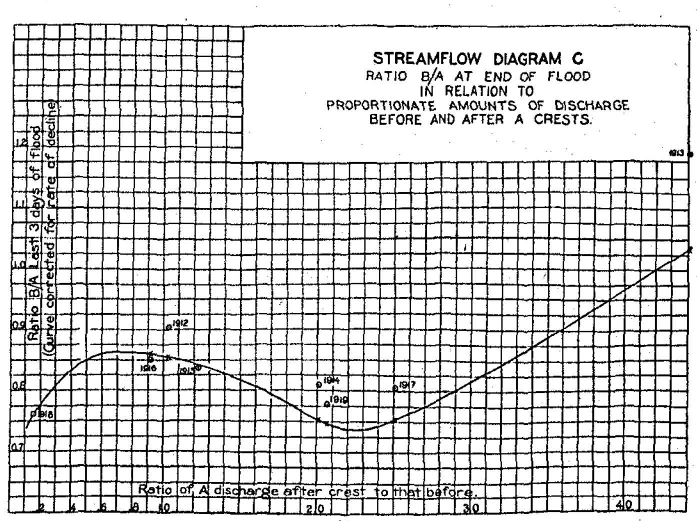

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FIG. 27.

TABLE 39.—*Normal rate of decline.*

[Days before end of flood.]

Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).
1........	0.003	9.......	0.039	17......	0.091	24......	0.162
2........	.007	10......	.044	18......	.099	25......	.175
3........	.011	11......	.050	19......	.108	26......	....
4........	.015	12......	.056	20......	.118	27......	....
5........	.019	13......	.062	21......	.128	28......	....
6........	.024	14......	.069	22......	.139	29......	....
7........	.029	15......	.076	23......	.150	30......	....
8........	.034	16......	.083				

The crest of the flood.—Both the relative time of the crests on the two streams and their relative heights will be found of importance in allocating the discharge during the flood period. Two relations stand out clearly in all of the records:

1. The crest on B always comes later than the crest on A. This is, apparently, due to slower melting on B than on A, for, if melting is suspended when stream A has reached a high point, but while there is considerable snow remaining, the later use of B is more marked than that of A, and, in consequence, the *highest day* for B may be many days later than that for A.

Normally—that is, when melting goes on continuously and the crest on A is sharp and well-defined—the crest on B follows within a day or two, the lag resulting from slower melting on B being almost balanced by its ability to make quicker delivery of the water.

2. The crest on B is higher than that on A unless materially delayed. This usually stands out more markedly in the decade averages than in daily amounts, because the large volume is better sustained in the case of B.

In further evidence of the first point, we may safely say that the crest on B will not be delayed more than two or three days after the highest day for A, unless, on the latter date, there is sufficient snow unmelted to produce an appreciable, secondary rise on A. The crest on B will usually follow this secondary rise within a day or two. This is illustrated in Table 40,[10] the crest on B not coming until 13 days after the last rise of A. Because of this, it is not deemed best to calculate the time of B crest from these data.

TABLE 40.—*Data relating to time of B crest.*

Year.	Crest on A.		Secondary rise on A.				Delay in B crest (days).
	Date.	Rate (C. F. S.).	Date.	Rate (C. F. S.).	Number of days.	Amount of come-back (inches).	
1912..........	May 20	1.642	....	....	....	0	2
1913..........	Apr. 16	.379	May 1	0.337	15	.088	26
1914..........	May 11	.680	May 15	.649	4	.034	5
1915..........	May 19	.751	....	....	0	0	1
1916..........	May 11	.906	....	....	0	0	3
1917..........	May 18	2.206	June 4	1.529	17	.328	19
1918..........	May 6	.157	May 20	.118	14	.000	15-16
1919..........	May 6	.893	May 15	.682	9	.043	11

[10] The year 1913, which was peculiar in many respects, is a marked exception to the rule.

In Table 41 and diagrams D, DD, and DDD are presented the more important data bearing (1) on the ratio B/A on the crest day for A, (2) on the time interval between A and B crests, and (3) on the relative height of the B crest.

Regarding (1):

Diagram D shows quite clearly that the relative height of Stream B on the crest day for A depends largely on the proportion of the whole flood that has been discharged up to that time.

B will be practically as high as A if the melting has been quite regular and the crest is reached promptly, and is followed by a similar regular decline, or, in other words, if about half the volume has been discharged by crest day.

B will be in a low ratio to A if the rise shortly before the crest has been unusually rapid, leaving more than half the flood to be discharged.

The relative position of B may, again, be low if more than half the volume has been discharged by crest day, because of slow melting before A crest. In 1918 the relatively large volume before the crest is partly the result of choosing a higher discharge rate for the end than for the beginning of flood calculations. This difference, of course, is not so important when the volume is large.

Regarding (2):

The time interval between A and B crests is, again, seen to be related to the proportion of the whole flood that has been discharged before A crest. It is a logical corollary of what has just been said—the higher the ratio B/A on the crest day for A, the less the time that must elapse before B reaches its crest. No further explanation of this point seems necessary.

Regarding (3):

The exact height reached by B at its crest, relative to the A crest, is readily seen to be dependent on temporary melting conditions as well as those conditions which have brought B to a certain point at the time when A crests. It will depend not only on the rate of melting, but upon the amount of snow remaining to be melted. After many futile efforts to determine the height of the B crest directly, on the basis of conditions similar to those which seem to determine the height of B when A crests, it has been decided that the cresting of Stream A really represents a culmination of influences for both streams, and we must, therefore, predicate the height of the B crest upon the height which this stream has reached at the A crest, together with a measure of the amount of influence that may yet be felt by B from late-melting snow, or possibly new precipitation, during the interval between the two crests. This is best measured by the behavior of Stream A. We may readily assume that if the latter is not appreciably influenced by either melting snow or new precipitation, it will decline from its crest in such a manner as to form a very regular curve, each day's flow being a function of that of the day before. Thus, if the rate declined 10 per cent each day, the constant function K could be expressed by $K=0.90$. The aggregate flow for any number of days following the crest, whose rate we may express by H, might be expressed by

$$\Sigma e = HK + HKK + HKKK, \text{ etc.}$$

This is merely a suggestion as to the nature of the decline. The summation of daily quantities may actually best be expressed as a function of the crest height and the time or $\Sigma = H \times T^{4/5}$.

If the flow of A is actually high, during the early declining period, relative to this calculated flow, we may expect that B will have an opportunity to gain considerably over its height on the crest day for A. Such a calculation permits us to compute the crest height of B very closely, except for such a year as 1918, but, it must be remembered, the calculation is based on two values which can not be directly read, namely, the height of B on A crest day, and the time elapsing between crests.

TABLE 41.—*Relation of streams at A crest and relative time and height of B crest.*

Year.	Date.	Crest day on A.				
		A rate.		B rate inches (O. W.)	Ratio B/A this date.	Percentage A flood discharged to date.
		C. F. S.	Inches O. W.			
1912	May 20	1.642	0.1757	0.1734	0.988	49.2
1913	April 16	.379	.0405	.0182	.448	18.4
1914	May 11	.680	.0728	.0551	.758	33.2
1915	May 19	.751	.0804	.0801	.997	44.9
1916	May 11	.906	.0971	.0866	.892	52.2
1917	May 18	2.206	.2362	.1620	.686	28.5
1918	May 6	.157	.0168	.0117	.697	86.4
1919	May 6	.893	.0957	.0724	.756	32.7
Average	May 10	....	....	....	....	....

Year.	Crest day on B.					Actual discharge A since crest (inches O. W.)	A crest rate times 4/5 power of days.	Ratio actual to theoretical flow of A after crest.
	Date.	Time since A crest (days).	B rate.		Ratio to rate on A crest day.			
			C. F. S.	Inches O. W.				
1912	May 22	2	1.966	0.2336	1.348	0.3308	0.3059	1.081
1913	May 12	26	.339	.0403	2.215	.8050	.5488	1.468
1914	May 16	5	.723	.0861	1.564	.3367	.2634	1.278
1915	May 20	1	.681	.0811	1.013	.0758	.0804	.943
1916	May 14	3	.948	.1127	1.301	.2586	.2339	1.105
1917	June 6	19	1.692	.2011	1.242	2.6706	2.4895	1.074
1918	May 21-22	15–16	.110	.0131	1.120	.2142	.1505	1.425
1919	May 17	11	.948	.1127	1.557	.8320	.6518	1.278

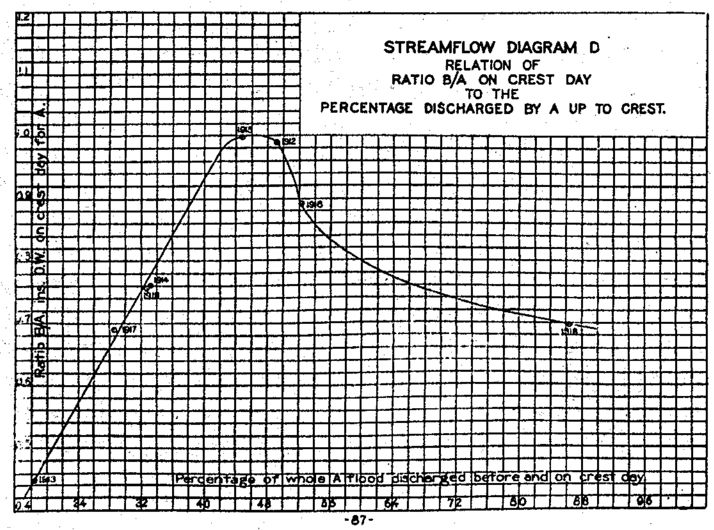

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FIG. 28.

RULE 4. *To determine the suppositional period elapsing between the crests of streams A and B, calculate the total amount discharged by Stream A in its flood and the percentage of this discharged up to and including the crest day. By reference to diagram DD the probable time between A and B crests may be read directly.*

RULE 5. *To determine the probable ratio B/A, in inches over watershed, on the crest day for A, follow the same procedure as in Rule 4, referring the discharge percentage to diagram D.*

RULE 6. *To determine the suppositional height of the crest on B in relation to the height of B on the crest day for A (as determined by rule 5), multiply the discharge rate of A on its crest day, by the 4/5 power of the number of days elapsing between crests (as determined by rule 4), and divide this quantity into the actual discharge of A for the days following the A crest and including the day of the B crest. The height of B crest, relative to its height on A crest day, will be relatively great if this actual flow of A is large in proportion to the head reached by A and the time interval, as shown by diagram DDD.*

Volumes discharged in flood.—In the preceding discussions we have merely been attempting to show the relative heights of the two streams at various critical periods, in order that the suppositional flood volume of B, under any conditions occurring in the future, might be properly allocated as to time. So far as this is possible, it permits the dividing of the flood into any number of subperiods, as might be desirable, if, as in 1917, the flood period should be extended to the first of August. It is realized that the temporary relationships on which such alloca-

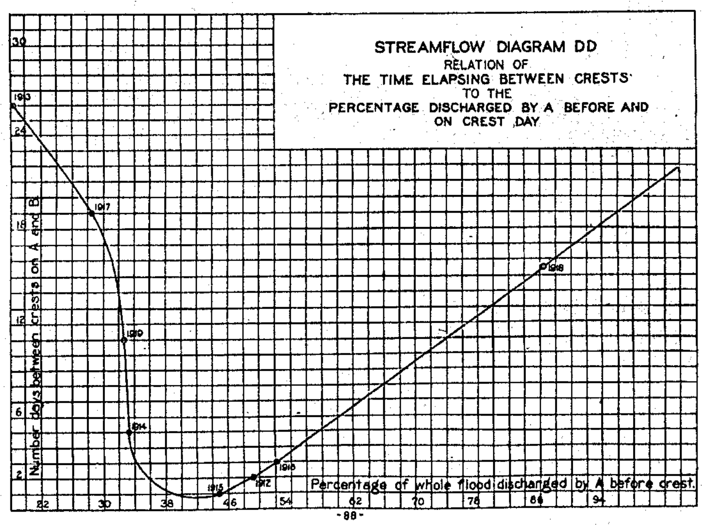

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FIG. 29.

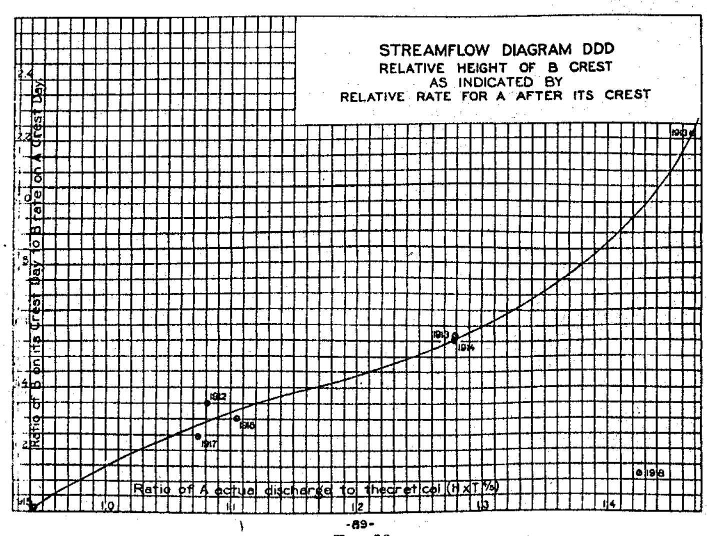

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FIG. 30.

tion must be based are subject to variations which can hardly be anticipated, yet it is believed that these will be of relatively small magnitude, and considering that all such temporary volume as may be computed for B will be subject to the check against total discharges during the flood period, there is left practically no opportunity for serious error.

At first glance the total volumes discharged by the two streams seem to stand in very simple relationships, with one or two insignificant exceptions, as shown by diagram E. The total volumes, from the first rise above 0.100 C. F. S. to the final dip to 0.150 C. F. S., stand in almost a straight-line relationship, being equal when the flood discharge is 7 inches and only slightly greater for A than for B at lower values. The year 1913 is the only important exception, the flood being maintained by considerable precipitation for an unusually long period, considering the height of the crest. The crest date was also very early, leaving much snow unmelted at that time.

On closer examination it is found that the ratios between total volumes in the flood are subject to the same conditions as those which fix the ratios of the two streams at cresting time. Strange it seems, however, that a sharp crest and an evenly balanced flood which produce the highest ratio B/A at the crest, give us the lowest relative discharge of B for the whole flood. The one fact is not the *cause* of the other, but both are probably the result of rather late and rapid warm-weather melting.

Diagram EE shows that this method of computing relative flood volumes may aid greatly in obtaining a precise value, though the course of the curve beyond the line of 50 per cent is entirely problematical.

The relative volumes discharged up to the time of the crest on A are also very regular, but it must be noted that during this first half of the flood A *always* has the advantage, by one-third for small volumes and decreasing to about one-seventh for the highest volumes.

As has been pointed out, the crest on A seems to represent a culmination of the conditions which tend to keep the two streams in a steady relationship. As a result, the relative volumes computed up to the time of the B crest are not so regular. Generally, in the interval between crests, B discharges more than A, tending to bring the volume ratio, up to B crest, more nearly 1 : 1. It is not suggested that this control be used in future compilations, except when the B crest is long delayed and there is a considerable volume involved which can not be readily allocated according to Rules 4, 5, and 6. The data relating to flood volumes are given in Table 42 and diagrams E, EE, EEE, EEEE.

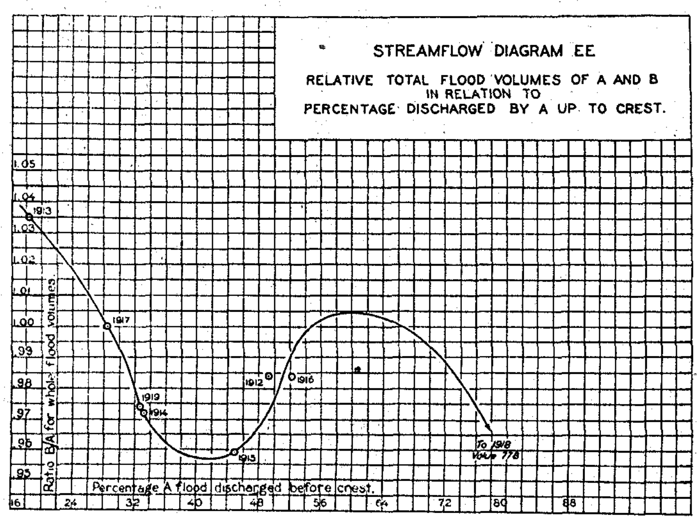

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FIG. 32.

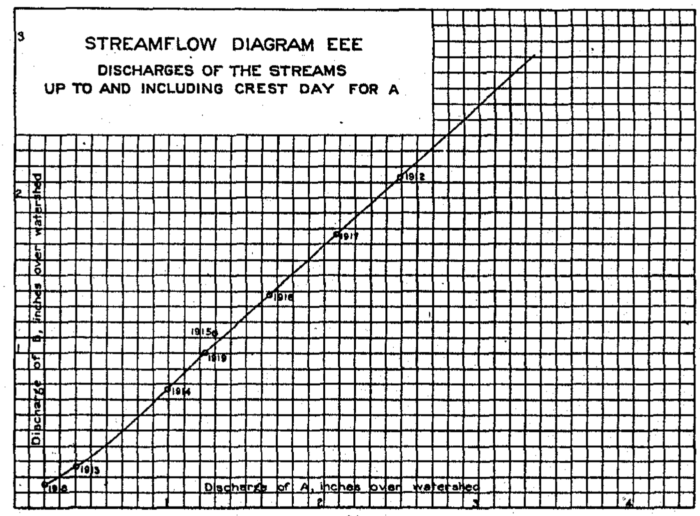

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FIG. 33.

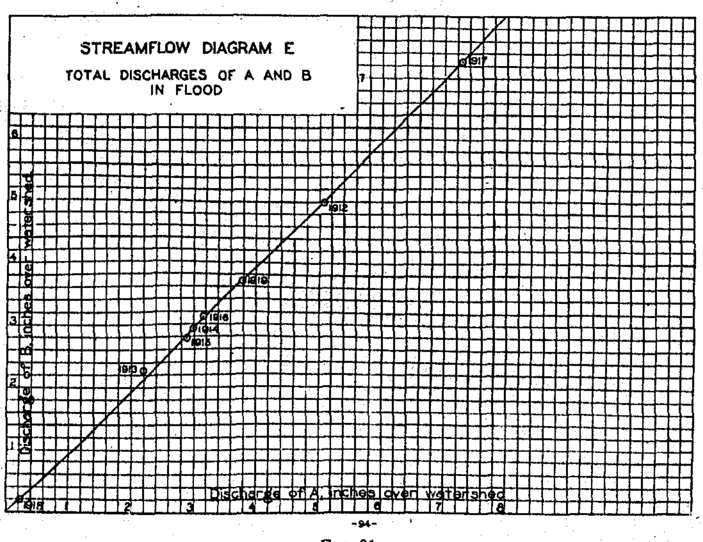

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FIG. 31.

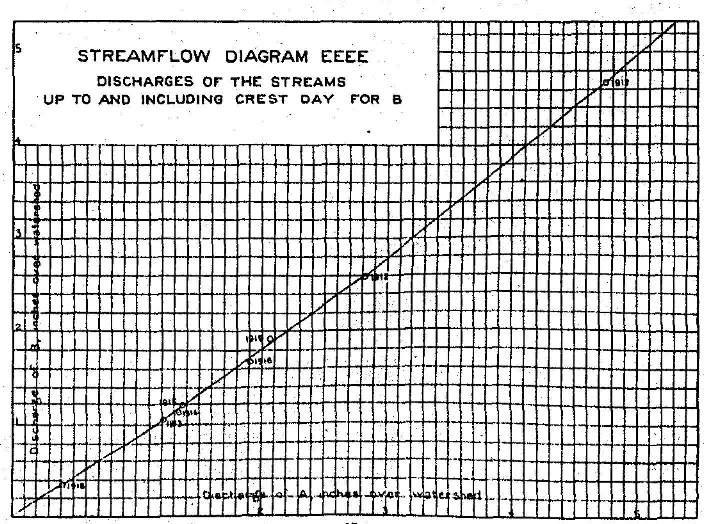

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FIG. 34.

TABLE 42.—*Summary of flood volumes.*

Year.	Stream.	Critical dates.			Duration (days).	Amount discharged (inches O. W.).		
		First.	Last.	Highest.		Before C.	After C.	Total.
1912	A	Mar. 6	July 19	May 20	136	2.4947	2.5782	5.0729
	B			May 22		2.1302	2.8586	4.9888
1913	A	Mar. 29	June 28	Apr. 16	91	.4060	1.7930	2.1990
	B			June 12		.2460	2.0130	2.2770
1914	A	Apr. 5	July 5	May 11	91	.9971	2.0061	3.0032
	B			May 16		.7652	2.1545	2.9197
1915	A	Apr. 12	July 4	May 19	83	1.2943	1.5884	2.8827
	B			May 20		1.1311	1.6363	2.7674
1916	A	Mar. 10	June 22	May 11	104	1.6481	1.5131	3.1615
	B			May 14		1.3777	1.7321	3.1101
1917	A	Mar. 29	Aug. 2	May 18	126	2.0735	5.1922	7.2657
	B			June 6		1.7669	5.4966	7.2635
1918	A	Apr. 23	May 8	May 6	15	.2031	.0321	.2352
	B			May 21–22		.1579	.0241	.1820
1919	A	Apr. 4	July 5	May 6	92	1.2354	2.5491	3.7845
	B			May 17		1.0031	2.6823	3.6854
Average	A	Mar. 30	June 30	May 10	92	1.2941	2.1565	3.4506
	B			May 20		1.0745	2.3247	3.3992

Year.	Stream.	Ratio B/A.		Discharge between crests.[1]		Percentage up to A crest.
		Before crest.	Whole flood.	Current.	Total.	
1912	A	0.854	0.984	0.3308	2.8255	49.2
	B			.4504	2.5806	42.8
1913	A	.650	1.035	.8050	1.2110	18.4
	B			.7820	1.0460	11.6
1914	A	.767	.972	.3367	1.3338	33.2
	B			.3659	1.1311	26.2
1915	A	.895	.959	.0758	1.3701	44.9
	B			.0811	1.2122	40.9
1916	A	.835	.984	.2586	1.9070	52.2
	B			.3075	1.6852	44.3
1917	A	.851	1.000	2.6706	4.7441	28.5
	B			2.9006	4,6669	24.4
1918	A	.776	.773	[2] .2142	.4173	86.4
	B			.1893	[2] .3472	86.8
1919	A	.811	.974	.8320	2.0674	32.7
	B			.9096	1.9127	27.2
Average	A			.6905		
	B			.9482		

[1] Most of this volume accrued outside the technical flood period, which ended 2 days after the crest on A.
[2] After crest day for A, but including crest day for B.

RULE 7. *To determine the suppositional relative volume discharged by stream B during the whole flood period, beginning with the first day in spring when A has a rate of more than 0.100 C. F. S., and ending on the last day in which this rate is 0.150 C. F. S. or more, refer the computed discharge of A to diagram E, from which the approximate B volume may be directly read. For a more precise measure of the B volume, refer the percentage discharged by A up to its crest, to diagram EE, from which the relative B volume may be read.*

RULE 8. *To determine the suppositional flood volume for B, from the first day of flood up to and including the highest day for A, refer the computed volume for stream A to diagram EEE, from which the corresponding value for B may be directly read.*

RULE 9. *In the event that conditions are such as to delay the crest of B, as determined by rule 4, more than 5 days beyond the crest on A, and the discharge curve for A is so irregular as to make the intervening section of the B curve questionable, the suppositional volume for B, for the period between crests, may be obtained by computing the total flood volume for A up to the suppositional date of B crest, and referring this to diagram EEEE, the corresponding volume for B may be read. The volume for B between crests will be the last figure reduced by the amount of the volume determined by rule 8.*

The summer rainy period.—The most casual inspection of the ratios between the two streams after the close of the flood period and during the summer months, shows that these are influenced more largely by conditions existing during the flood than by current conditions. In other words, the summer period must be considered an extension of the flood period.

Plotting the values by months, it is seen that immediately following the flood, the ratio B/A generally declines, that is, B declines somewhat more rapidly than A, as it did during the last stages of the flood. After about August 1, however, there is generally an increase in this ratio, which tends to approach unity about October 1. Table 43 gives the general data for the summer period.

If only the ratios for summer days without rain are plotted, the early decline is less marked, but rather regularly the lowest basic ratio is reached close to August 1. It therefore seems only logical to consider as the first section of the summer period the time from the end of the flood to the end of July, when the general tendency is downward.

The effect of rain during this summer period is to depress the ratio B/A. If there is a considerable fall in any one day the depression is quite great, showing that stream A discharges immediately a larger proportion of each rain. If rains continue for several days, however, B gains exactly as it does in the later periods of the spring flood, and the ratio tends to move back to its basic dry-weather value.

TABLE 43.

Year.	Last day of flood.	W.	Run-off and precipitation after flood, inches O. W.					
			May.		June.		July.	
			P.	R.	P.	R.	P.	R.
1912	July 19	A					2.56	0.2121
		B						.1873
1913	June 28	A			0.00	0.0307	2.30	.3558
		B				.0356		.3779
1914	July 5	A					4.56	.4063
		B						.3131
1915	July 4	A					2.30	.3369
		B						.2823
1916	June 22	A				.1167	5.10	.4072
		B				.0975		.3254
1917	Aug. 2	A						
1918	May 8	A	0.13	0.2961	1.10	.2884	3.82	.8208
		B		.2807		.2839		.8129
1919	July 5	A					3.83	.3946
		B						.2967

Year.	Last day of flood.	W.	Run-off and precipitation after flood, inches O. W.						Ratio B/A for whole period.
			August.		September.		Total.		
			P.	R.	P.	R.	P.	R.	
1912	July 19	A	1.76	0.4133	0.043	0.3230	4.75	0.9484	0.956
		B		.3843		.3351		.9067	
1913	June 28	A	2.34	.2642	2.43	.2622	7.07	.9129	1.059
		B		.2741		.2783		.9659	
1914	July 5	A	2.25	.3626	1.40	.3042	8.21	1.0731	.822
		B		.2906		.2779		.8816	
1915	July 4	A	1.80	.2949	2.83	.2530	6.93	.8848	.892
		B		.2585		.2475		.7883	
1916	June 22	A	3.01	.3730	1.50	.3029	9.61	1.1998	.866
		B		.3231		.2920		1.0380	
1917	Aug. 2	A	2.10	.3862	1.21	.3203	3.31	.7065	.854
				.3155		.2874		.6029	
1918	May 8	A	3.05	.2015	3.07	.2399	11.17	1.2622	1.013
		B		.2154		.2505		1.2786	
1919	July 5	A	1.02	.3090	1.43	.2554	6.28	.9590	.894
		B		.2899		.2702		.8568	

Summer relations to the end of July—From what has been said, it is evident that the relation of the two streams during this period must be based on flood conditions. In fact, a number of attempts to treat the summer period independently have proved absolutely futile. The basis which naturally suggests itself is the same as that used to determine the ratio at the end of the flood, namely, the proportionate discharge before and after the crest of the flood.

The ratio for the period ending July 31 may, in fact, be based either upon the relative amount after the crest to the end of the flood, or the amount after the crest and to the end of July, but this is probably only a coincidence, as a basis similar to the former does not produce good results in August and September. It has, therefore, been deemed advisable to use a mean ratio for July, and similar ratios for August and September, each based on the status of the flood discharge at the beginning as well as the end of the period. In each case, a correction must be applied for the amount of precipitation since the end of the flood.

Throughout this period, as has been noted, the general effect of precipitation is to depress the ratio B/A, and, since there is a tendency for the relationship to be depressed anyway, owing to the draining-out of B and perhaps greater evaporation on that area while the trees are in foliage, the effect of precipitation, then, is to place the relationship of the two streams in a position such as would exist without this precipitation at a later stage of discharge. In other words, the corrections for precipitation may, in all cases, be applied as direct additions to the discharge ratios of A for the particular period in question.

In Table 44 and diagram F are presented the data for the period ending July 31. Since the 1917 flood did not terminate until August 2, that year can not, of course, be considered here.

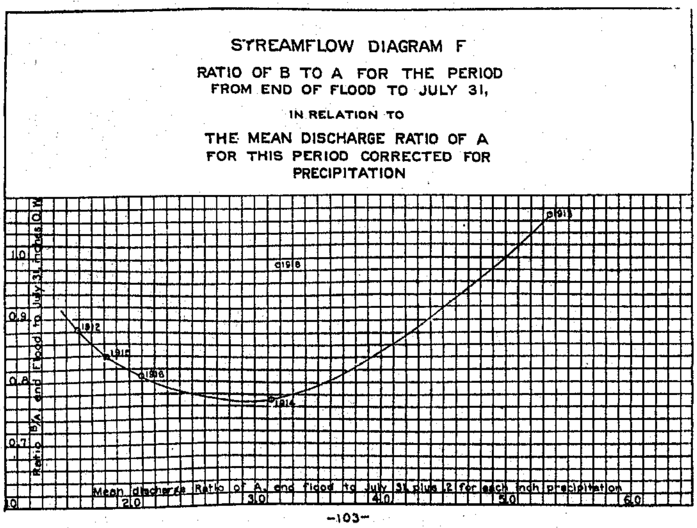

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FIG. 35.

TABLE 44.—*Stream flow relation from end of flood to July 31.*

	A discharge ratio.			Precipitation to July 31.	Correction for precipitation.	Corrected discharge ratio.	Ratio B/A to July 31.
	To end flood.	To July 31.	Mean.				
1912	1.033	1.119	1.076	2.56	0.512	1.588	0.883
1913	4.420	5.350	4.890	2.30	.460	5.350	1.070
1914	2.016	2.420	2.218	4.56	.912	3.130	.771
1915	1.227	1.489	1.358	2.30	.460	1.818	.839
1916	.918	1.236	1.077	5.10	1.020	2.097	.808
1917	2.504	....	....	....	....	....	....
1918	.158	4.196	2.177	5.05	1.010	3.187	.990

RULE 10.—*To determine the suppositional ratio of B to A streamflow, in inches O. W., for the period from the end of the flood to July 31, first determine the amount of A discharge from the crest to the end of the flood, and the similar amount from the crest to the end of July, expressing each quantity as a function of the amount discharged before the crest: to the mean of these two functions, add 0.2 for each inch of precipitation on watershed A occurring between the end of the flood and the end of July. The corrected function, or ratio of A discharges, when referred to diagram F, will give the suppositional ratio B/A for the period ending July 31.*

Relations in August.—The streamflow relations in August appear to be controlled much the same as those of the period ending July 31, namely, by the status of the flood discharge during this period. Precipitation occuring prior to August undoubtedly has some permanent effect, while that which occurs in August is not as effective currently as was precipitation in the earlier period. Consequently, good results are obtained by using a correction factor which amounts to 10 per cent of the total precipitation for August and the preceding period. The basis for diagram G is shown in Table 45.

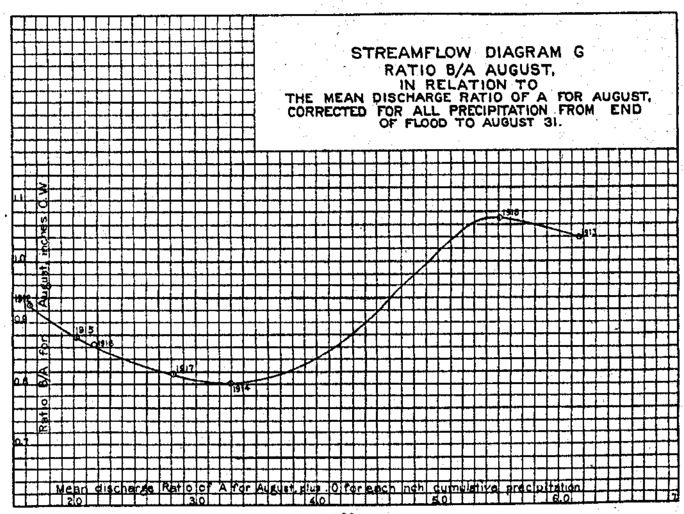

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FIG. 36.

TABLE 45.—*Streamflow relations for August.*

Year.	A discharge ratios.			Precipitation end of flood to end of August.	Correction for precipitation (0.10).	Corrected discharge ratio.	August discharges (inches O. W.).		
	To end of July.	To end of August.	Mean for August.				A	B	Ratio B/A.
1912	1.119	1.285	1.202	4.32	0.432	1.634	....	....	0.930
1913	5.360	6.018	5.689	4.64	.464	6.153	....	....	1.038
1914	2.420	2.784	2.602	6.81	.681	3.283	....	....	.802
1915	1.489	1.717	1.603	4.10	.410	2.013	....	....	.877
1916	1.236	1.462	1.349	8.11	.811	2.160	....	....	.866
1917	2.504	2.690	2.597	2.10	.210	2.807	....	....	.817
1918	4.196	5.188	4.692	8.10	.810	5.502	....	....	1.069

Rule 11.—*To determine the suppositional ratio of B to A streamflow, in inches O. W., for August, determine the mean discharge ratio of A for this period, as described for the preceding period, and to this ratio add 0.1 for each inch of precipitation from the end of the flood to August 31. The corrected ratio, when referred to diagram G, will give the desired result.*

Relations in September.—As has been stated, the ratio B/A usually tends to approach unity toward the end of the summer season. This is believed to be, at least in part, due to a cessation of transpirational water loss from the large areas of aspen on B. It may, however, be a natural result of reaching an advanced stage in the draining out of the spring flood water.

The effect of current precipitation in September is *nil*, or possibly to a slight extent the opposite of its effects earlier in the season, since now B is generally ascending, relative to A, while, if it has any effect at all, precipitation should tend to keep B down. Good results are obtained, as shown in Table 46 and diagram H, by entirely ignoring the September precipitation, but correcting the flood ratio by the same amount as in August.

Dry-weather conditions at end of September.—As has been pointed out, the two streams tend to approach a unity ratio in October, stream B rising in response to decreasing evaporation. It is of interest, therefore, although it does not seem to assist in other calculations, to see how the ratios stand during the last few days of September, when dry weather usually prevails. For the purpose of this examination we have added together the discharges of all days, of each year, between September 26 and 30, which were devoid of rain.

On comparing the discharges of the streams for these periods, it is found that their relationships still reflect the influence of the summer rains. The curve of ratios for the several years, however, is very much flattened in comparison even with that for the whole month of September. September precipitation seems to be reflected as an influence in an opposite direction from that of rainfall earlier in the summer. The results are shown in Table 47 and diagram I.

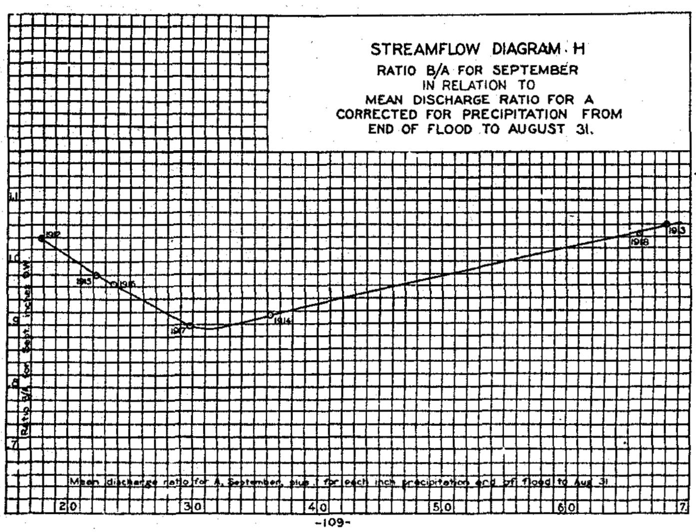

Fig. 37.

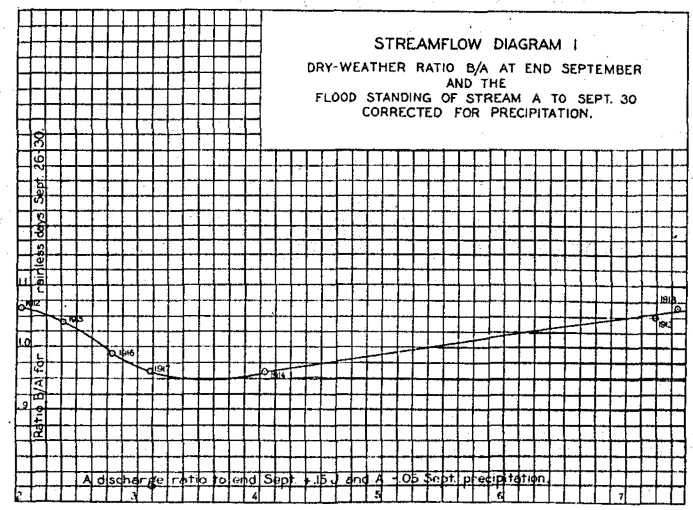

Fig. 38.

Table 46.—*September streamflow relations.*

Year.	A discharge ratios.			Precipitation.		Correction for precipitation (0.10).	Corrected discharge ratio.	September discharges (inches O. W.).		
	To end of August.	To end of September.	Mean for September.	End of flood to Aug. 31.	September.			A	B	Ratio B/A.
1911..	......	......	......	......	......	......	......	......	......	......
1912..	1.285	1.414	1.350	4.32	0.43	0.432	1.782	......	......	1.038
1913..	6.018	6.662	6.340	4.64	2.43	.464	6.804	......	......	1.061
1914..	2.784	3.086	2.935	6.81	1.40	.681	3.616	......	......	.913
1915..	1.717	1.913	1.815	4.10	2.83	.410	2.225	......	......	.979
1916..	1.462	1.646	1.554	8.11	1.50	.811	2.365	......	......	.965
1917..	2.690	2.843	2.766	2.10	1.21	.210	2.976	......	......	.898
1918..	5.188	6.360	5.774	8.10	3.07	.810	6.584	......	......	1.045
1919..	2.633	2.836	2.734	4.85	1.43	.485	3.219	......	......	1.059

Rule 12.—*To determine the suppositional ratio B/A for September, both discharges in inches over watershed, compute the amounts discharged by A from the crest of its flood to August 31 and to September 30, expressing each quantity as a function of the amount discharged before the crest: to the mean of these two functions or ratios, representing an average stage for September, add 0.10 for each inch of precipitation from the end of the flood to August 31, disregarding September precipitation. The corrected ratio, when referred to diagram H, will show the desired ratio of B discharge to that of A.*

Table 47.—*Dry-weather relations at end of September.*

[Days without rain, Sept. 26–30.]

Year.	Stream.	Dry-weather discharges.				
		Number of days.	Total C. F. S.	Mean C. F. S.	Total inches, O. W.	Ratio B/A.
1911	A	4 23, 24	0.375	0.0938	0.0406	0.957
	B	25, 28	.327	.0818	.0388	
1912	A	5	.511	.1022	.0545	1.063
	B	26–30	.488	.0976	.0580	
1913	A	3 26, 28	.275	.0917	.0294	1.050
	B	29	.260	.0867	.0309	
1914	A	4 26–29	.369	.0922	.0396	.960
	B	....	.322	.0805	.0381	
1915	A	3 26–28	.258	.0860	.0277	1.040
	B	....	.242	.0807	.0288	
1916	A	5 26–30	.452	.0904	.0484	.989
	B	....	.402	.0804	.0478	
1917	A	4 26–29	.394	.0985	.0423	.962
	B	....	.343	.0858	.0407	
1918	A	5 26–30	.350	.0700	.0376	1.065
	B	....	.337	.0674	.0400	
Averages	A	....	....	.0906	....	1.01075
	B	....	....	.0826	....	

TABLE 47.—*Dry-weather relations at end of September*—Continued.

Year.	Stream.	A discharge ratio to Sept. 30.	Precipitation after flood— To Aug. 31 (+0.15).	Precipitation after flood— September (−0.05).	Correction for precipitation.	Corrected ratio B/A.
1911	A B	....	....	....	....	....
1912	A B	1.414	4.32	0.43	0.626	2.040
1913	A B	6.662	4.64	2.43	.574	7.236
1914	A B	3.086	6.81	1.40	.952	4.038
1915	A B	1.913	4.10	2.83	.471	2.384
1916	A B	1.646	8.11	1.50	1.141	2.787
1917	A B	2.843	2.10	1.21	.255	3.098
1918	A B	6.360	8.10	3.07	1.061	7.421

RULE 13. *To determine the suppositional ratio B/A for days without rain falling between September 26 and September 30, inclusive, first compute the ratio of all the discharge of Stream A after the flood-crest and up to September 30, in relation to that before and including the flood-crest. To this quantity add 0.15 of the precipitation (inches) from the end of flood to August 31, and deduct 0.05 of the precipitation for September. The result, referred to diagram I, will show the suppositional relation of the streams in inches O. W.*

Relations for the whole summer.—As a check upon the monthly calculations for the summer period, it is deemed advisable to compare the entire volumes discharged. On plotting these it is found that they form, for the several years, essentially a straight line, but there is sufficient divergence from a fixed relationship to make necessary more detailed consideration, the ratios for years varying from 0.821 in 1914 to 1.059 in 1913.

Treating the relations for the whole summer in the same manner as those for the individual months, it is found that a rather irregular curve may be drawn by plotting the ratios against the flood ratios for stream A, as previously, with a correction amounting to 0.2 of the precipitation for the whole summer. Why this correction should be larger than in any month except July it is a little difficult to see, but it is probably due to the fact that both July precipitation and run-off represent larger volumes than those of later months.

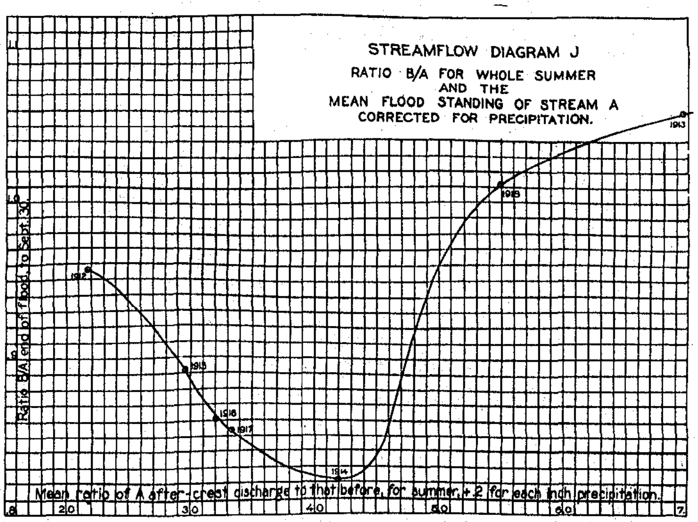

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FIG. 39.

TABLE 48.—*Relation of streams for whole summer period.*

[End of flood to Sept. 30.]

Year.	Total summer discharges (inches O. W.). A	Total summer discharges (inches O. W.). B	Total summer discharges (inches O. W.). Ratio.	A discharge ratios. End of flood.	A discharge ratios. End of September.	A discharge ratios. Mean for summer.	Total precipitation from end of flood.	Correction for precipitation (0.20).	Corrected discharge ratio.
1911	....	....	....	....	....	....	....	....	....
1912	0.9484	0.9065	0.956	1.033	1.414	1.224	4.75	0.950	2.174
1913	.9129	.9659	1.059	4.420	6.662	5.541	7.07	1.414	6.955
1914	1.0731	1.8816	.821	2.016	3.086	2.551	8.21	1.642	4.193
1915	.8848	.7883	.892	1.227	1.913	1.570	6.93	1.386	2.956
1916	1.1998	1.0330	.861	.918	1.646	1.282	9.61	1.922	3.204
1917	.7065	.6029	.854	2.504	2.843	2.674	3.31	.662	3.336
1918	1.2622	1.2784	1.012	.158	6.360	3.259	11.17	2.234	5.493
1919	.9590	.8568	.894	2.061	2.836	2.448	6.28	1.256	3.704

RULE 14.—*To determine the suppositional ratio B/A, in inches over watershed, for the entire period from the end of the flood to September 30, take the mean of the flood-discharge ratios of stream A, representing the end of the main flood and the end of September, respectively, and to this quantity add 0.2 of the precipitation in inches for the period from the end of the flood to September 30. The result referred to diagram J will show the relation of the streams for the whole summer. In the event that the suppositional discharge of B so computed is either more or less than the sum of the B discharges for the periods ending July 31, August 31, and September 30, the two quantities will be averaged and the increase or decrease in the sum will be prorated to the three periods in accordance with their respective volumes as previously computed.*

The fall and winter storage period.—The previous discussions have been concerned with the seasons in which, at least at low elevations, the water from mountain streams may have a positive value for irrigation purposes. The period from October 1 of any year to the beginning of the spring flood of the following year may properly be considered as a period of storage in which, if it were possible stream flow should be reduced to a minimum, so as to conserve the water for the next season of growth. This is actually what is happening in most of the Rocky Mountain region by reason of the fact that precipitation after October 1 is mainly in the form of snow, after November 1 there is only a small amount of melting. An important exception to this rule occurred in the present experiment, in the heavy rains at the beginning of October, 1911; and also, on the watersheds in discussion, there is melting on the exposed southerly slopes at all times during the winter. It is probable, however, that little of the snow melted thus slowly replenishes the streams, and that much which appears to be melted is directly evaporated.

During this entire fall and winter period, Stream B is continuously discharging more than Stream A, although at the end of September the ratio B/A may still be slightly below unity. This high discharge of B, as has been pointed out, may be due to its receiving slightly less insolation on slopes exposed fully to the sun, and consequently having a lower evaporation factor; it may be due to a larger area of deciduous trees on B, giving less opportunity for winter transpiration; or it may be largely the result of the flow from a single spring whose source is so deep as to be little affected by winter temperatures.

It seems logical, as well as most convenient, tentatively to treat the entire fall and winter season as one period in the computations, in which it will be possible to show whether a denuded watershed is storing less water, or more water, for flow at a time when it may be used. It is recognized, however, that this method may not permit the proper integration of all the factors affecting winter flow and, therefore, if a more satisfactory, detailed method is later worked out, it will certainly be used.

Since October 1 has been selected as the beginning of the stream-flow year, it is desirable, if possible, to break away from the control which appears to govern the relation of the two streams during the summer, though the writers feel by no means convinced that flood conditions may not still be reflected in October and later. The amount of the discharge of A in October has been taken as the basis for comparison, partly because it will reflect in some degree the extent to which the flood waters have been drained out, and partly because the volume of flow involved probably determines, as much as anything else, the degree of effect of cold weather upon the two streams. It is self-evident that a given amount of melting, which may produce a larger effect on one stream than on the other, can not affect the percentage relation of the two so greatly if the discharge rate is relatively high as with a low discharge rate.

In the preceding section it has been shown that severe freezing weather has a more marked effect in decreasing the flow of A than it does in the case of B. Such effects, however, are temporary, and are probably entirely offset by the release of ice-bound supplies later. For the entire winter period, therefore, the ratio B/A is high when the temperatures are relatively high.

In order that the October rate of flow, which shall be the basis for comparing the streams, may represent a rate whose influence will be carried through the winter, it seems desirable to decrease the actual discharge of A by a certain amount of the October precipitation, whose temporary influence only is felt in the October run-off. This

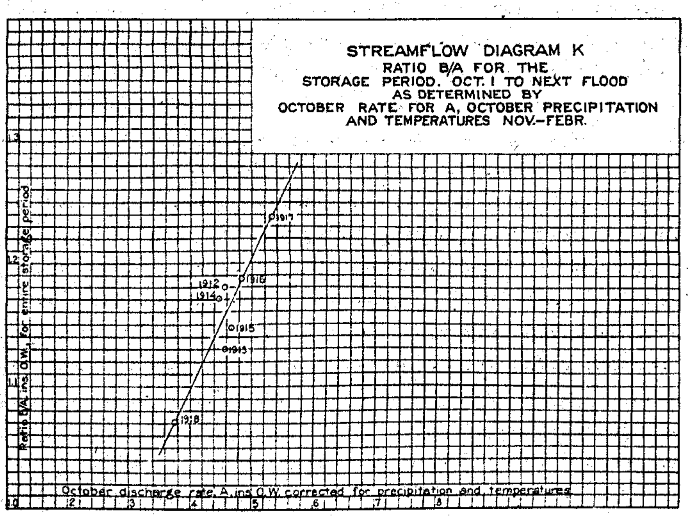

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FIG. 40.

percentage has been arbitrarily assumed to increase with the amount of precipitation, and is shown by 1 per cent of the first inch, 2 per cent of the second inch, 3 per cent of the third inch, etc.

The correction of the October discharge rate on account of the temperatures from November to February, inclusive, is a positive correction; that is, with high temperatures. There is a relatively high ratio B/A for the winter, as would be the case if the initial discharge rate had been higher.

The data for the winter period are given in Table 49 and diagram K.

TABLE 49.—*Streamflow for fall and winter period and relations as affected by temperature and October precipitation.*

Year.		Discharges during winter months (inches O. W.).							
		October.	November.	December.	January.	February.	March.	April.	Total.
1911–12....	A	0.9015	0.4564	0.3673	0.3120	0.2671	[2]0.0465	....	2.3508
	B	.9844	.4337	.3621	.3363	.3065	.0523	....	2.4753
1912–13....	A	.3393	.3003	.2862	.2782	.2268	[3].2386	....	1.6694
	B	.3798	.3501	.3382	.3284	.2886	.2849	....	1.9700
1913–14....	A	.2871	.2552	.2498	.2417	.2163	.2712	[4]0.0387	1.5600
	B	.3069	.2900	.2882	.2810	.2475	.3023	.0455	1.7614
1914–15....	A	.3080	.2387	.2264	.2591	.2185	.2406	[5].1025	1.5932
	B	.3158	.2912	.2875	.2979	.2614	.2853	.1224	1.8615
1915–16....	A	.2740	.2454	.2258	.2199	.2068	[6].0675	....	1.2394
	B	.2808	.2713	.2688	.2692	.2484	.0818	....	1.4203
1916–17....	A	.4242	.3418	.2540	.2360	.2115	[3].2155	....	1.6830
	B	.4583	.3829	.3231	.3040	.2661	.2622	....	1.9966
1917–18....	A	3174	.2718	.2533	.2337	.2017	.2225	[7].2043	1.7047
	B	.3217	.3139	.3121	.3031	.2956	.3161	.2460	2.1085
1918–19....	A	.2381	.2226	.2229	.2170	.1914	.2231	[4].0287	1.3438
	B	.2528	.2410	.2376	.2338	.2065	.2377	.0296	1.4390

Year.		Ratio B/A.	Mean rate A discharge per day.	October precipitation.		Mean temperature November to February.		Corrected October rate A discharge.
				Amount.	Correction for.[1]	Degrees.	Correction for (plus 0.01).	
1911–12........	A	1.053	0.01497	4.41	0.1205	16.45	0.1645	0.9455
	B	....	....	....	....	....	....	....
1912–13........	A	1.180	.00932	2.53	.0459	16.40	.1640	.4574
	B	....	....	....	....	....	....	....
1913–14........	A	1.130	.00844	0.93	.0093	18.02	.1802	.4580
	B	....	....	....	....	....	....	....
1914–15........	A	1.170	.00826	2.21	.0363	17.50	.1750	.4467
	B	....	....	....	....	....	....	....
1915–16........	A	1.147	.00774	0.36	.0036	19.70	.1970	.4674
	B	....	....	....	....	....	....	....
1916–17........	A	1.187	.00940	4.31	.1155	17.55	.1755	.4842
	B	....	....	....	....	....	....	....
1917–18........	A	1.237	.00835	0.19	.0019	21.70	.2170	.5325
	B	....	....	....	....	....	....	....
1918–19........	A	1.071	.00726	1.06	.0112	14.92	.1492	.3761
	B	....	....	....	....	....	....	....

[1] Minus 1 per cent of first inch, 2 per cent of second, 3 per cent of third, etc.
[2] Mar. 5. [3] Mar. 28. [4] Apr. 3 [5] Apr. 4. [6] Mar. 9. [7] Apr. 22.

RULE 15. *To determine the most probable ratio B/A for the period beginning October 1 and extending to the last day before the spring flood of the following year, add to the flow of stream A for October, in inches over watershed, 1 per cent of the mean temperature for the four months of November, December, January, and February (determined arithmetically from monthly mean hourly temperatures at station A-1), and from this sum subtract 1 per cent of the first inch of October precipitation, 2 per cent of the second inch or fraction, 3 per cent of the third, and so on. The result referred to diagram K will indicate the ratio B/A for the whole period in question, with a probable error of less than 1 per cent.*

Erosion and silt deposition in basins.—It has been explained that the dams are so constructed as to form basins in which either stream is given opportunity to deposit whatever of silt and soil has been picked up along its course. The amount of time for settling naturally decreases as the rate of discharge increases, so that it is not surprising to find that in high stages the amount of lighter organic material is much less than in quiet stages. This is clearly brought out in Table 50 in the so-called "humus" percentages. In brief, the high water of the spring flood is not only capable of carrying heavier and coarser material than is carried at other times, but also high water may tend to carry the lightest material past the settling basin. All of the systematic and complete measurements on the accumulations of silt in the basins are given in Table 50.

TABLE 50.—*Amounts of silt deposited in basins and relations between A and B.*

Collection of —	Dam A.		Dam B.		Ratio, B weight / A weight
	Weight.	Humus.	Weight.	Humus.	
	Pounds.	*Per cent.*	*Pounds.*	*Per cent.*	
1913—July 16, 15	226.0	28.5	267.0	14.5	1.180
Oct. 15, 14	106.0	25.9	94.0	21.5	.887
1914—Apr. 22, 21	129.0	34.6	99.0	27.7	.767
July 14, 15	180.0	29.8	156.1	12.7	.866
Oct. 16, 15	84.1	34.4	198.0	12.9	2.354
1915—Apr. 14, 9	324.6	28.8	233.8	16.0	.720
July 16, 15	292.7	20.8	335.0	8.5	1.145
Oct. 15, 15	67.0	29.5	103.3	17.6	1.542
1916—Apr. 18, 12	138.2	32.2	132.1	20.2	.955
July 17, 14	195.5	25.1	312.0	7.5	1.595
Oct. 14, 17	115.6	39.0	350.8	11.7	3.035
1917—Apr. 16, 17	278.1	26.8	203.2	10.9	.731
July 17, 16	1,257.6	21.1	542.7	8.4	.432
Oct. 15, 15	43.3	22.8	62.1	20.0	1.435
1918—Apr. 16, 16	150.3	27.3	84.4	31.0	.562
July 17, 16	88.7	28.3	67.1	27.3	.756
Oct. 15, 16	82.8	34.5	84.8	31.2	1.025
1919—Apr. 16, 14	84.0	35.5	71.1	30.9	.846
July 15, 16	192.4	22.0	143.1	14.0	.744
Averages—Apr. 15	184.0	30.9	137.3	22.8	.764
July 15	347.6	25.1	260.4	13.3	.960
Oct. 15	83.1	31.0	148.8	19.2	1.713

In Diagram L it has been sought to express directly the relationships between the amounts deposited by streams A and B. These relationships are so evidently different for the winter, flood, and summer periods that it is necessary to consider separately the regular measurements of April 15, July 15, and October 15.

It is hardly to be questioned that more satisfactory explanations of the variations in silt deposits of either stream could be obtained by relating each to the total or maximum discharge for each period. But this would have the objectionable feature that in the future the most probable deposition of stream B would have to be related to its most probable discharge, and it seems very undesirable so to complicate the calculations. Therefore, the matter of silt deposits is kept distinct.

The relation of B deposits to A deposits is not constant, even for corresponding periods of different years, and there is no satisfactory explanation for the variations.

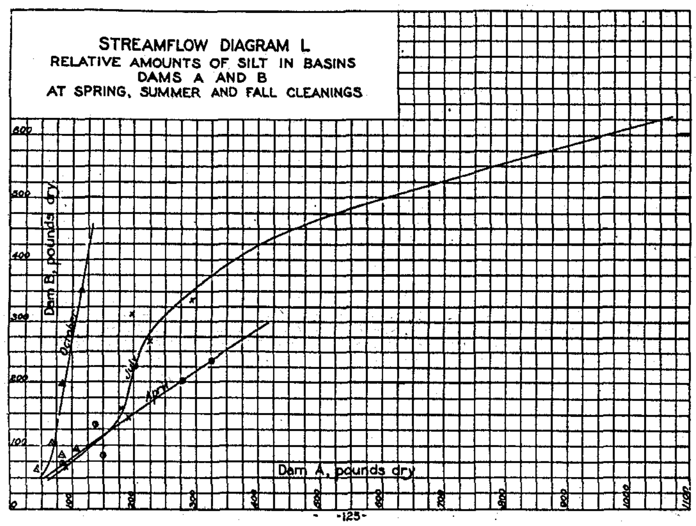

FIG. 41.

However, the values lend themselves fairly well to expression by graphs, and in the event that future records should go beyond the scope of these, it is believed the average ratios given in Table 50 might well be used for the calculations.

RULE 16. *To determine the most probable amount of dry silt, in pounds, that would have been deposited by stream B, had the watershed not been denuded, refer the amount deposited by stream A to the proper graph of Diagram L, according to whether the amount is for the period ending April 15, July 15, or October 15. From this graph the amount for B may be read directly.*